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MODE S SYSTEM ACCURACY

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16. Abstract

A series of flight tests were performed using three Mode S (formerly the Discrete Address Beacon System (DABS)) sensors for the purpose of determining the capability of each sensor in reporting the true position of an aircraft. For both the Mode S and the Air Traffic Control Radar Beacon System (ATCRBS) mode of operation, slant range, and azimuthal position data, as reported by each sensor, were compared to positional data collected concurrently by a precision range instrumentation system at the Federal Aviation Administration (FAA) Technical Center.

Results related to the Mode S sensors at the Technical Center and Clementon, New Jersey, satisfied the jitter requirements of 50 feet (range), and 0.1° (azimuth), although slight degradation of the Mode S azimuth accuracy occurred at high elevation angles above 20°. Position data for the Elwood, New Jersey, sensor were affected by the alignment characteristics of the front and back antenna configuration associated with the long-range radar facility.

Areas requiring further investigation are related to the relatively high bias value of the slant range residual for all three sensors: compensation of the range delays due to aircraft instrumentation, short-term and long-term drift of the azimuth residual, and the alignment problems associated with the front-to-back antenna configuration at the long-range radar facility at Elwood.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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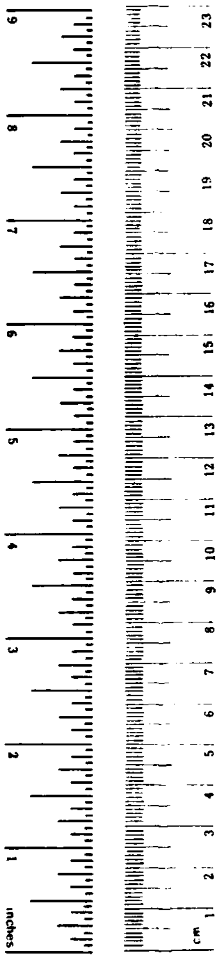
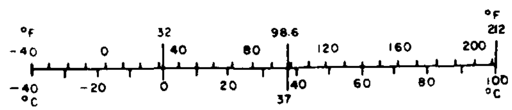


Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

The purpose of this test and evaluation (T&E) activity was to ascertain the accuracy with which the Mode S (formerly the Discrete Address Beacon System (DABS)) reports the spatial position of Mode S and Air Traffic Control Radar Beacon System (ATCRBS) transponder equipped aircraft.

BACKGROUND.

The requirement for the development of Mode S was identified in the 1969 Department of Transportation Air Traffic Control Advisory Committee (ATCAC) Study. A feasibility study and validation of the Mode S concept was conducted by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory. After successfully demonstrating the feasibility of the Mode S concept, an engineering requirement, FAA-ER-240-26 (reference 1), was prepared by Lincoln Laboratory for the development of three single channel Mode S sensors which could operate as a network and interface with terminal air traffic control (ATC) facilities.

A procurement contract was awarded to Texas Instruments, (TI) Incorporated, to provide three Mode S sensors for T&E at the Federal Aviation Administration (FAA) Technical Center. The three sensors were installed at the following locations:

1. Terminal sensor at the FAA Technical Center Airport Surveillance Radar (ASR-7) facility.

2. Terminal sensor at Clementon, New Jersey (N.J.), Airport Surveillance Radar (ASR-8) facility.

3. En route sensor at Elwood, N.J., Air Route Surveillance Radar (ARSR-2) facility.

In June 1979 the MITRE Corporation conducted tests to determine the range and azimuth accuracy of the Technical Center Mode S terminal sensor. The results of these tests are documented in MITRE Report No. MTR-80N00002, "Surveillance Positioning Accuracy of the Discrete Address Beacon System" (reference 2).

This report expands the scope of the effort performed by MITRE in three areas:

1. All three Mode S sensors were subjected to accuracy testing.

2. Radial and orbital flight tests were selected to further optimize the accuracy of the spatial reference tracking radar data after geometric conversion to the site of each Mode S sensor.

3. An increased number of data samples were processed to reduce statistical errors associated with small sample size tests.

DISCUSSION

SYSTEM DESCRIPTION.

The Mode S is a secondary radar system with both surveillance and communication capabilities. It is designed as an evolutionary improvement over the existing ATCRBS within the ATC environment. FAA reports FAA-RD-74-189 and FAA-RD-80-41 (references 3 and 4) contain a complete functional description of Mode S, and also define several of the design improvements. One of these design improvements is the enhanced aircraft-position determination that results from the use of a monopulse antenna design and associated receiver/processing aspects of the Mode S surveillance capability.

Monopulse azimuth accuracy is verified through the incorporation of a special test transponder at each sensor. This transponder, referred to as calibration performance monitoring equipment (CPME), is permanently installed at a surveyed location within the coverage area of its associated sensor.

The aircraft position data, expressed in slant range and azimuth, become part of a target report that is compiled during each antenna scan and then remoted to ATC facilities. Complete details of the message formats for each target report are shown in report FAA-RD-74-63A (reference 5). The following descriptions are limited to the Mode S technique of determining the slant range and true azimuth of the aircraft relative to the sensor location.

RANGE ESTIMATION. As with conventional ATC radar systems, the measurement of elapsed time between reference interrogation pulses and transponder replies permits a determination of the slant range of a target. The Mode S design provides for range unit increments of 0.0625 microseconds. With this capability, the time of transmission for each ATCRBS and Mode S interrogation is recorded for later comparison with the time-of-arrival of a specific reply pulse to obtain an estimate of the two-way range delay, expressed in range units. This two-way range delay, which includes aircraft antenna cable and transponder reply delays, is then converted to a slant range value prior to insertion within the target report. Range units for the two-way target reports are converted to one-way range units by dividing by two and truncating any remainder since fixed point arithmetic is used for computations. This increases the one-way quantization for slant range measurements from approximately 30 to 60 feet.

The recorded time reference is the leading edge of the transmitted pulse for ATCRBS targets. Comparison of this time reference to the real-time clock at receipt of the leading edge of the F1 pulse of the ATCRBS reply train provides the total two-way range delay. For Mode S roll-call interrogations, the transmission time reference point is the first sync phase reversal of the P6 pulse, which is then compared to the time-of-arrival of the first preamble pulse from the transponder reply.

AZIMUTH ESTIMATION. The initial acquisition of a Mode S-equipped aircraft is accomplished during the same period as an ATCRBS/Mode S all-call interrogation; but once the Mode S target is acquired and placed in a roll-call file, the Mode S interrogation/reply sequence is accomplished by the use of the transponder assigned discrete code during a time frame that is separate from the ATCRBS interrogation period. Interrogation transmission and reply reception for both Mode S and ATCRBS targets are accomplished using a common 5-foot ATCRBS antenna configured to produce "sum" and "difference" patterns required by the monopulse design. This design utilizes the ratio of the signal amplitudes (difference/sum) to determine the off-boresight alignment value. This alignment value, in conjunction with the antenna boresight azimuth value from the azimuth pulse generator, provides an angular measurement of target position that is related to true north. The azimuth calibration bias adjustment is accomplished by reference to the surveyed azimuth value for the CPME location. This adjustment occurs in increments of 0.022° since the azimuth pulse generator provides 16,384 pulses, or 14 bits, for each antenna revolution.

OBJECTIVE.

The overall test objective was to determine the capability of the Mode S sensor to report the position of an aircraft target relative to the location of the sensor. Specific objectives were to compare the sensor target reports to the coordinate converted positional data concurrently obtained from the Nike/Hercules (hereafter referred to as Nike) radar tracking system. The slant range reported from the Mode S sensor, minus the coordinate converted range from the tracker, is defined as the range residual. Likewise, the azimuth angle reported by Mode S, minus the converted tracker azimuth angle, is defined as the azimuth residual. These objectives and definitions apply to both the Mode S and ATCRBS mode of operation.

METHODOLOGY.

Installation of the three Mode S sensors within the test environment of the FAA Technical Center was accomplished to satisfy the terminal and en route operation requirements of the overall test and evaluation effort. However, the relationship of each sensor to the location of the reference Nike aircraft-tracking system is critical in ensuring the optimum performance of the reference tracker. To this end, specific flight patterns were designed for each individual sensor. Each sensor operated in a single-site test configuration to preclude any data interruptions due to acquisition of the target by an adjacent sensor (Mode S network management function). Therefore, throughout the remainder of this report data collection and reduction are in reference to the single-site test configuration.

SINGLE-SITE TEST CONFIGURATION. Figure 1 depicts the functional relationship between the sensor and the Nike tracking system. Data recording at the Mode S sensor (data extraction subsystem) and the Nike tracking system were time-correlated by requiring time-synchronization with a common source, such as the National Bureau of Standards (NBS) transmission from station WWVB at Boulder, Colorado. Within the test aircraft were three transponders: a Mode S transponder, an ATCRBS transponder capable of responding to Mode S interrogations, and an X-band transponder designed solely for use with the Nike tracking system. Thus, aircraft positional data were collected by the sensor in the Mode S and ATCRBS mode of operation for comparison with precise aircraft-positional data obtained concurrently by the Nike tracking system.

NIKE/HERCULES TRACKING SYSTEM. Precision tracking of the test aircraft was accomplished using a modified military instrumentation radar, referred to as the Nike tracking system. This Nike tracking system is capable of tracking two targets simultaneously using a target tracking radar (TTR), and a missile tracking

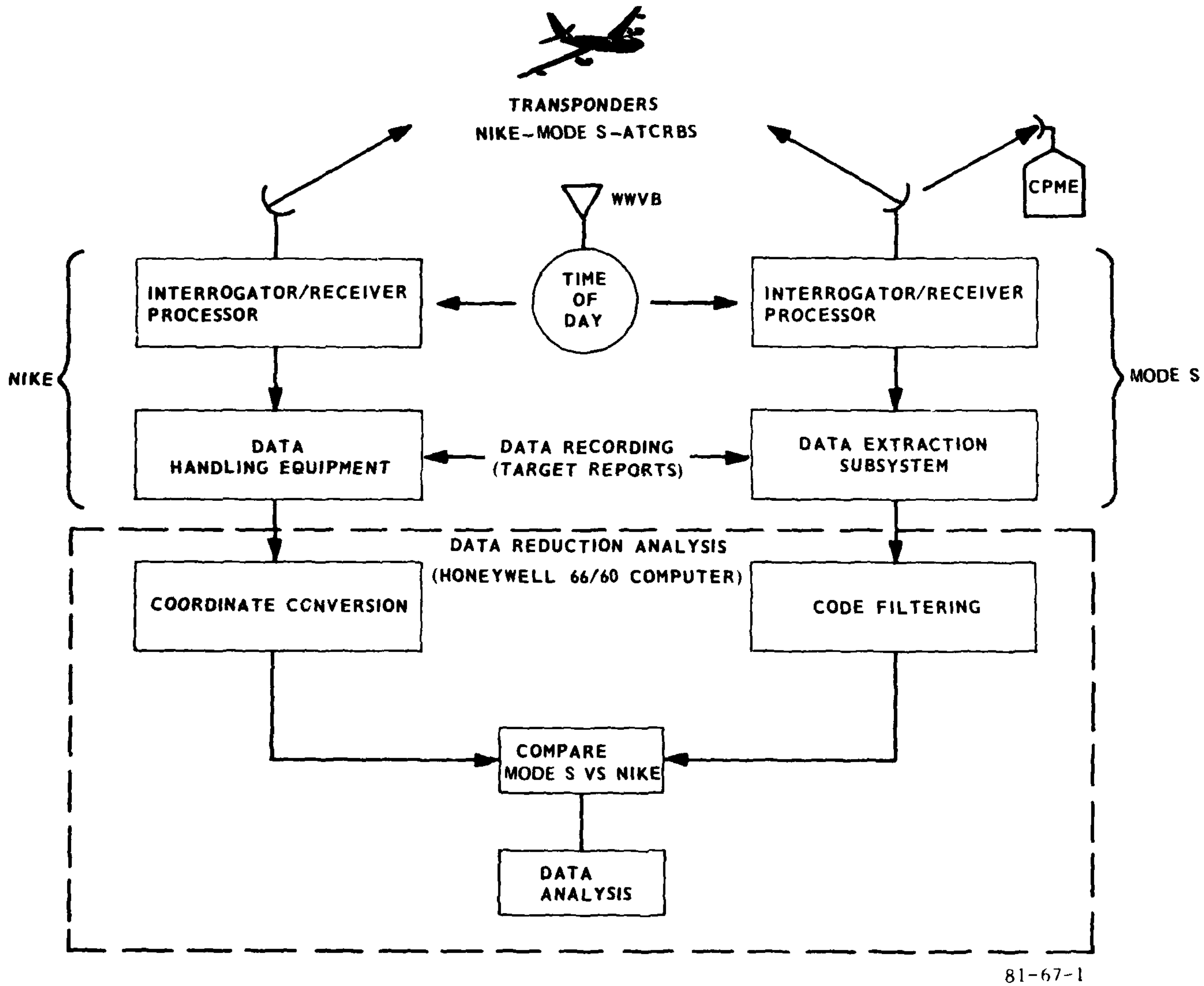


FIGURE 1. SINGLE SITE TEST CONFIGURATION

radar (MTR). Although an X-band transponder common to both tracking radars was installed in the test aircraft to provide for maximum utilization of the dual-target tracking function, all data in this report were obtained with the TTR.

All positional data, recorded at the Nike tracking system, include a time-of-day entry that is synchronized with the transmission from the NBS station WWVB at Boulder. Positional information from this tracking system is provided to the Mode S data reduction program (see figure 1) in a latitudinal and longitudinal format, which is then coordinate converted to the precise location of each sensor site in a form compatible with the output data from the Mode S sensor.

The Nike tracking system provides aircraft positional data at a rate of 10 reports each second. These data are subsequently time-correlated with the Mode S and ATCRBS reports which occur once per antenna revolution. The theoretical error budget for the Nike tracking system is shown in table 1. However, for the purpose of this report, the Nike tracking system is assumed to be an absolute reference.

TABLE 1. THEORETICAL ERROR BUDGET FOR THE NIKE/HERCULES TRACKING SYSTEM

	Theoretical Bias Error	Theoretical Random Error
Azimuth	0.25 Milliradians (0.014°)	0.15 milliradians (0.008°)
Elevation	0.25 Milliradians (0.014°)	0.15 Milliradians (0.008°)
Range	3 Meters	6 Meters

Complete details in reference to the capabilities of the Nike tracking system are listed in report No. FAA-NA-79-32 (reference 6).

CALIBRATION/ALIGNMENT.

Calibration of the range and azimuth functions within each sensor requires special procedures, as outlined in the FAA engineering requirement (ER) FAA-ER-240-26, to assure precise reporting of the true position of the aircraft. This is accomplished by using the CPME surveyed location and its inherent delay characteristics for initial-sensor calibration. Alignment of the sensor antenna boresight is performed by adjustment of the azimuth pulse generator to reflect the CPME sensor-surveyed azimuth value. The range calibration requires consideration of both the surveyed range value, the CPME cable length, and transponder reply delays. This range calibration has to be accomplished in the three modes of operation: ATCRBS replies to ATCRBS/Mode S all-call interrogations, Mode S all-call replies, and Mode S roll-call replies.

SITE SURVEYS. The positional coordinates for each of the Mode S sensors and their respective CPME were obtained under a Second Order, Class II Survey, as defined by the Federal Geodetic Control Committee. The survey reference point for each terminal radar sensor was the center line of its radar antenna, whereas, the lower radar beacon antenna (front antenna) was the reference point for the en route facility. For each CPME, the survey reference point was the center line of its feedhorn. The survey values for each sensor and CPME met the requirements of ±0.0028° for azimuth, ±5-foot for position, and ±1-foot for elevation. These values were subsequently verified using a satellite surveying system, the Navy Navigation Satellite System (NNSS).

CPME PROCESSING DELAYS. Range calibration of each sensor against its respective CPME required the inclusion of those CPME delays that are additional to the actual survey range of each CPME in order to obtain a range delay value that represents total delay between the sensor and CPME. These additional values are the result of the CPME antenna cable propogation delay and any uncompensated CPME reply delay. Therefore, each CPME was subjected to special measurements to obtain the precise time-delay values that have to be considered in the determination of the total range delay.

TIME-OF-DAY SYNCHRONIZATION. Mode S target reports were available on a scan-by-scan basis and time-tagged for later comparison with Nike tracking data that were available every 0.1 second. To obtain maximum correlation for each comparison, it was necessary to have a common source for synchronization of the time-of-day reference at each facility. At the sensor, this was accomplished at the Mode S central clock subsystem, which was in continuous sync with the NBS coordinated universal time transmissions from Boulder (WWVB). Each Mode S sensor clock had the capability of maintaining a phase lock with the WWVB transmissions for a specified accuracy of ±0.0005 second.

AIRCRAFT INSTRUMENTATION. The aircraft used for these tests was a Convair 880 (N-42) that was capable of performing the high altitude flights necessary for collecting optimum Nike tracking data. Onboard the test aircraft there was a Mode S transponder (serial No. 203) capable of responding in the Mode S mode, and a TRU-1 ATCRBS transponder (serial No. 34) responding in the ATCRBS mode. This enabled both Mode S and ATCRBS data to be collected simultaneously by the Mode S sensor during each test flight. Aircraft cable and transponder delays were physically and electrically measured at the Technical Center avionics laboratory and subtracted from the range output data in order to determine the accuracy of each sensor independent of aircraft instrumentation delays. The aircraft instrumentation delays used during these accuracy tests are shown in table 2.

TABLE 2. N-42 AIRCRAFT INSTRUMENTATION DELAYS

	Transponder Delays (μs)			Cable Delay (μs)	Antenna Correction (Versus Nike Antenna)
	Nominal*	Actual	Correction	(One Way)	(Feet)
ATCRBS (No. 34)	3.0	3.050	+0.050	+0.055 (27 ft)	-4.4
Mode S (No. 203)	128.000	128.230	+0.230	+0.134 (66 ft)	-29.6

*The transponder delay times specified in the Mode S and ATCRBS National Standards are 128 ±0.25 μs for Mode S roll-call and 3 ±0.5 μs for ATCRBS.

Also onboard the test aircraft was an X-band transponder that responded only to interrogations from the Nike tracking system. Since the Mode S and ATCRBS transponder antennas were not colocated on the aircraft with the X-band transponder antenna, it was also necessary to compensate for this geometric difference. Table 2 also depicts the actual antenna correction values that were used during this test.

DATA COLLECTION/REDUCTION.

For specific radial and orbital flights, the Mode S and ATCRBS target reports formulated by the sensor for the test aircraft were recorded by the data extraction subsystem located at each sensor. The actual time-of-day that the aircraft target detect occurred was recorded to permit time correlation with aircraft positional data obtained from the Nike tracking system. Comparing the sensor target reports to the Nike tracking system reports resulted in a difference number (residual) which was used to calculate sensor accuracy.

The nominal transponder delays, converted to slant range, represent the corrections applied by the Mode S sensor for all ATCRBS and Mode S transponders regardless of type. Since the Mode S data extraction tapes contain corrections for nominal delays, the difference between the actual measured delay and the nominal delay is adjusted in the data reduction software.

SENSOR DATA. Slant range and azimuth positional data for each target were contained within a surveillance message that is transferred to the remote ATC facilities, as described in report FAA-RD-74-63A (reference 6). The recordings of these surveillance messages were accomplished at the data extracting subsystem with each sensor operating in a single-site mode to minimize the probability of interference from an adjacent Mode S sensor. Thus, the recorded data represents optimum sensor data exclusive of any delays and supporting data from adjacent sensors.

To minimize any error due to propagation limitations of the Nike tracking system, the flight profiles were designed to assure adequate signal response and minimum multipath reflection.

DATA REDUCTION PROCEDURES. Data reduction was performed using the general purpose computer (Honeywell 66/60) located at the FAA Technical Center. Specific computer programs were prepared to perform the following:

1. Data extraction tapes were filtered for those ATCRBS and Mode S beacon codes related to each test flight. Surveillance data relative to these appropriate beacon codes, as well as the CPME codes, were recorded onto a filter tape.

2. CPME target reports were compared to the effective range and azimuth references based on the filter tape output. This comparison consisted of a 30-scan average for both range and azimuth errors obtained at 30-minute intervals throughout the test period. The CPME data represented the actual static data necessary for sensor quality control analysis in support of data comparison.

3. Aircraft target reports recorded on the filter tape for each antenna scan were compared to the Nike tracking system data recorded every 0.1 second using time-of-day as a time-correlated function. The range instrumentation data were already converted to the sensor coordinates prior to the comparison.

4. Analysis programs were developed to permit categorizing the data according to range, azimuth, and elevation angle. These programs provided statistics, histograms, and special outputs for future processing.

FLIGHT TEST PROGRAM. The flight tests chosen were based on tracker accuracies and aircraft position relative to the tracker and the Mode S sensor. All flights were restricted to elevation angles between the aircraft and the tracker of greater than 2.75° to eliminate reflection and interference. In addition, the heading of each flight was selected to preclude any obstructions, such as an adjacent range instrumentation building, from distorting the data. Six types of flights were conducted in an attempt to gather enough statistical information to draw conclusions about the parameters that might affect the accuracy results (e.g., elevation angle, azimuth angle, slant range, time quantization, inbound versus outbound flights, and CPME performance). Three of the six flights were radials in which the aircraft maintained a constant azimuth angle, enabling slant range and elevation angle effects to be investigated. The other three flights consisted of orbital arcs requiring a constant slant range so that effects of azimuth could be analyzed. Back and forth passes were planned for each type of flight at several altitudes to obtain elevation angle characteristics. All three sensors were employed during the flight test program to determine the characteristics of each sensor.

Figure 2 illustrates the approximate profile of the aircraft flights. The Technical Center Mode S sensor outbound radial flights commenced about 5 nautical miles (nmi) west of the sensor and finished about 55 nmi west along a 269° azimuth. The Elwood sensor outbound radials started 13.5 nmi southeast of the sensor and ended about 31 nmi southeast along a 151° azimuth. Clementon outbound radials covered a 25-nmi distance from about 30 to 55 nmi southeast of the sensor on a 134° azimuth. All azimuth headings were measured against true north. All radial flightpaths were flown at the azimuth angle that aligns the Nike tracker and the Mode S sensor with the aircraft flying closer to the tracker than to the sensor.

The Technical Center sensor orbital flights maintained a constant 13-nmi slant range around the Mode S sensor at an azimuth interval from 190° to 330°. This 140° arc was selected to minimize the tracker induced error upon conversion of the tracker data to the sensor's coordinate system. Seven altitudes were selected in order to provide adequate data samples for elevation angles from approximately 3° to 30°. The Elwood and Clementon sensor orbital arcs were flown perpendicular to a line connecting the sensor with the tracker. Aircraft altitudes of 13,000 to 39,000 feet yielded elevation angle data from approximately 2° to 12° at the Clementon sensor. The Elwood arcs were conducted at altitudes ranging from 3,500 to 35,000 feet, resulting in elevation angle data from about 2° to 20°.

QUALITY CONTROL. The flight planning and data collection techniques were selected with the purpose of removing or reducing the identifiable slant range and azimuth errors. The azimuth and range residuals, after accounting for all the known errors, become the best estimate of the true error. A slant range correction was performed for the Mode S and ATCRBS antenna locations in the N-42 Convair 880 aircraft, as related to the Nike TTR antenna position in N-42.

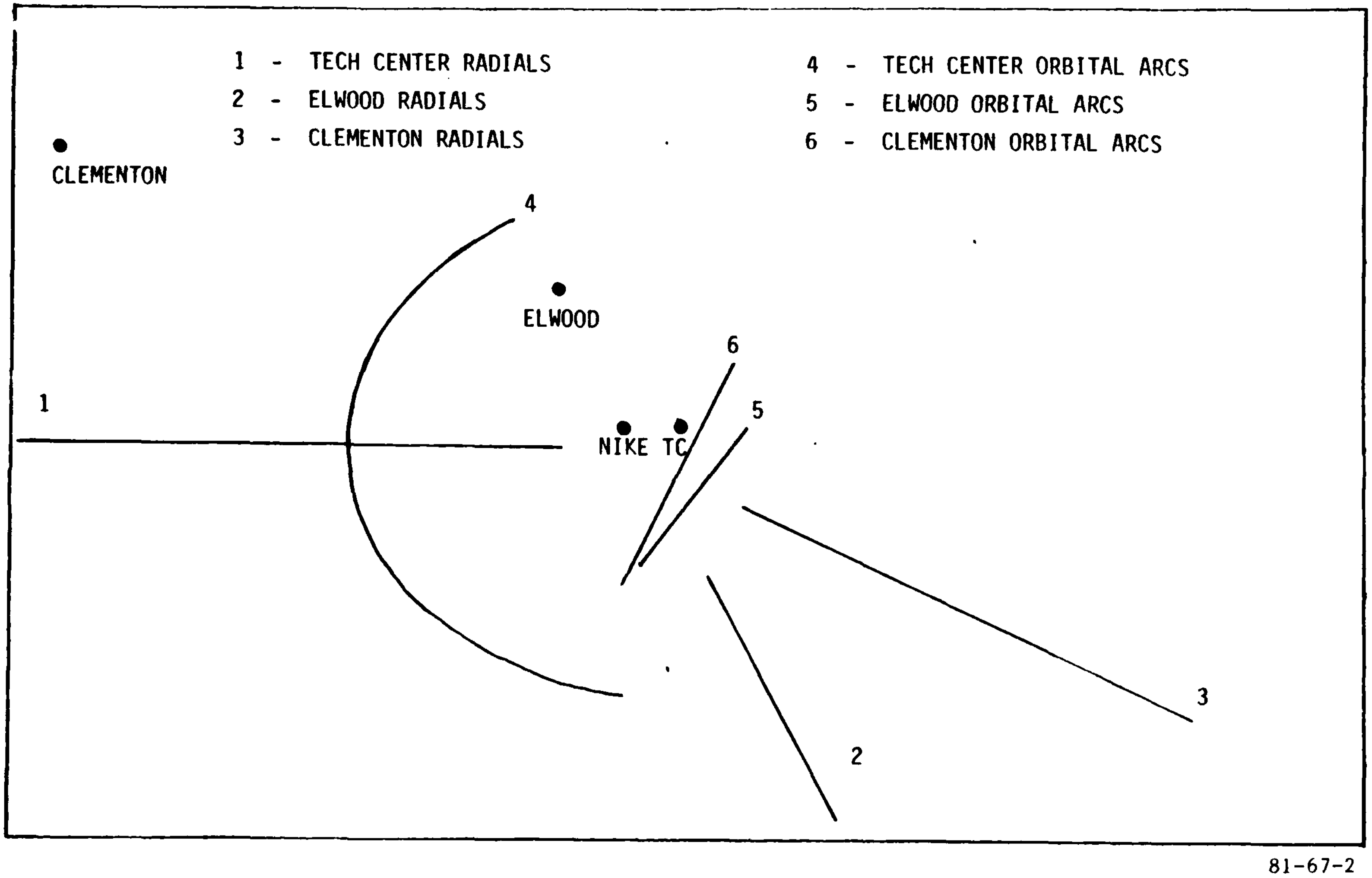


FIGURE 2. APPROXIMATE PROFILE OF FLIGHTS

DATA REDUCTION.

The initial phase of the data reduction process consisted of plotting the actual aircraft flights and comparing them to the test flight plan. All data recorded during aircraft turns were not processed. Any azimuth or slant range residual, obtained by subtracting the Mode S reported position from the translated Nike coordinate location, was considered an outlier if it exceeded six standard deviations from mean. Only 3 ATCRBS reports from the nearly 6,000 collected were considered outliers, 2 from the Technical Center sensor and 1 from Clementon. No Mode S reports were rejected. Approximately 3,000 data reports for Mode S and ATCRBS were recorded at the Technical Center sensor, and over 1,250 scans were recorded at Clementon.

SAMPLING THEORY. Statistical sampling techniques were utilized to determine a sample size requirement to ensure the credibility of the processed data residuals. Each mean residual contains a standard error due to sampling which can be represented as a 95 percent confidence interval. This sampling error is based on the number of samples, the statistical variance, and a selected confidence level. By estimating the variance, a sample size is computed to achieve a tolerable sampling error with 95 percent confidence using the formula:

$$\text{Sampling Error} = \frac{(1.96)^2 \text{ X Variance}}{\text{Sample Size}}$$

The test plan was designed to generate a significant number of samples for each elevation angle, azimuth angle, and slant range data group, thereby, reducing the statistical error due to sampling. The sampling errors for the combined azimuth residuals for elevation angles below 12.5° at the Technical Center and Clementon sensors were approximately 0.0014° for Mode S and 0.0019° for ATCRBS, based on more than 3,200 data samples. The sampling range errors for the same set of data were 1.9 feet for Modes S and 2.1 feet for ATCRBS. The largest error for any individual test flight was about 0.0042° for the azimuth residual sampling error, and about 3.3 feet for the range residual sampling error based on a 95 percent confidence level.

RESULTS AND ANALYSIS

The results and analysis presented in this section pertain to the two terminal sensors located at the Technical Center and Clementon. A software problem at the Elwood en route sensor affected the back face of the front/back configuration and caused inaccuracies in the azimuth residual data results. Limited results on the Elwood en route sensor are presented in appendix A.

TECHNICAL CENTER SENSOR.

Accuracy test data were collected at the Technical Center sensor during three flight tests. The first flight test consisted of five round-trip radial flights being flown at an altitude of 19,000 feet. The second flight test consisted of four round-trip radials at 39,000 feet. The third flight test consisted of orbital arcs from 190° to 330° azimuth at a slant range of 13 nmi and seven altitudes ranging from 4,000 to 39,000 feet, resulting in test data for elevation angles from 3° to 30°. Table 3 summarizes the azimuth and slant range residuals for Mode S and ATCRBS transponders on each of the three flight tests. For each flight test date, the total number of samples, the mean residual, and standard deviation were tabulated.

The Mode S and ATCRBS mean azimuth position relative to the tracker position was within 0.06° for all three flight tests. The Mode S azimuth residual standard deviations were approximately twice that for ATCRBS for elevation angles greater than 20°. (This is shown in table 4.) The ATCRBS data showed only slight changes based on elevation angle, while the Mode S results were strongly affected.

Figures 3, 4, and 5 contain Mode S and ATCRBS azimuth and slant range residual data histograms for the three flight tests. Each histogram groups all the data samples for a set of flights and provides the mean, standard deviation, the minimum/maximum residual, and the total number of antenna scans or data samples. The histograms of figures 3, 4, and 5 provide illustrations of the raw data distribution and the extreme values. Most of the histograms tend to be bell-shaped, except for the Mode S azimuth residual histograms. The Mode S azimuth residual histograms are skewed to the left because of a reduction in accuracy at the higher elevation angles due to the antenna beam pattern and the Mode S technique of requiring only a single reply per scan. The ATCRBS azimuth residual histograms show only minor skewness since it averages the two replies closest to the boresight, minimizing high elevation angle effects.

Mode S and ATCRBS azimuth residuals were plotted as a function of elevation angle, while slant range residuals were plotted against slant range for the constant azimuth radial flights (figures 6 and 7). Both figures show the azimuth residual decreasing as the elevation angle increases. This effect is much more pronounced for Mode S than for ATCRBS data. The range plots show slight increases in range residuals for both Mode S and ATCRBS as slant range increases. For the orbital flight tests, azimuth residuals were plotted in figure 8 based on elevation angle for the various altitudes tested. The Mode S and ATCRBS plots illustrate similar characteristics to those of figures 6 and 7. For all orbital flights, the slant range remained relatively constant, changing only slightly with each different altitude. The azimuth residuals did not change appreciably as the azimuth angle increased.

A comparison of azimuth residuals for outbound versus inbound flights showed no major differences for radial flights. The mean azimuth residuals for both Mode S and ATCRBS data are within one azimuth unit averaging only a 0.015° differential between outbound and inbound flights. For range residuals, the difference between Mode S and ATCRBS reports was approximately 150 feet with a 75-foot bias shift among the three tests. The standard deviation results for both Mode S and ATCRBS were within the 50-foot jitter requirement specified in the engineering requirements. The orbital flights provide the best comparison of range accuracies between clockwise and counter-clockwise flights. A difference of less than 2 feet indicates the flight direction had no significant impact on range accuracy for the tests analyzed. Although azimuth residual differences based on flight direction occurred, these differences are primarily attributed to time quantization effects.

TABLE 3. TECHNICAL CENTER SENSOR AZIMUTH AND SLANT RANGE RESIDUALS

Azimuth Residuals (deg)

			Mode S			ATCRBS		
Date (1980)	Test	No. Flights	No. Samples	Mean (deg)	Std Dev (deg)	No. Samples	Mean (deg)	Std Dev (deg)
7/1	19,000-ft radials	10	1,299	-0.032	0.062	1,289	0.036	0.030
7/23	39,000-ft radials	8	635	0.019	0.054	624	0.053	0.028
7/22	Orbital arcs	13	1,043	0.019	0.063	1,033	0.060	0.040

Slant Range Residuals (ft)

			Mode S			ATCRBS		
Date (1980)	Test	No. Flights	No. Samples	Mean (ft)	Std Dev (ft)	No. Samples	Mean (ft)	Std Dev (ft)
7/1	19,000-ft radials	10	1,299	-39	30	1,289	108	44
7/23	39,000-ft radials	8	635	-79	42	624	83	47
7/22	Orbital arcs	13	1,043	-114	22	1,033	33	31

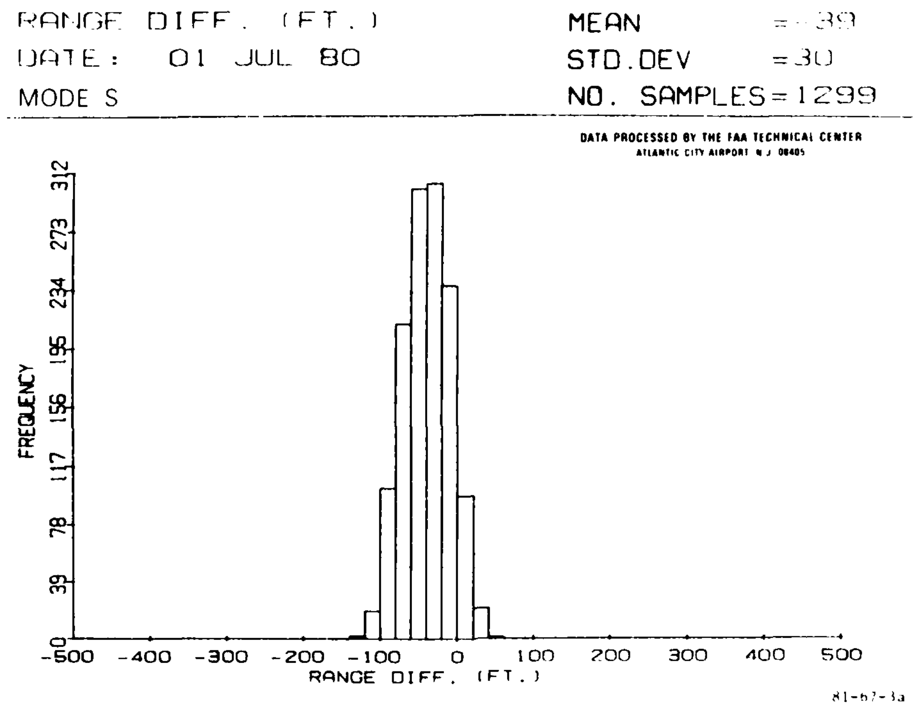
TABLE 4. TECHNICAL CENTER SENSOR AZIMUTH RESIDUALS ELEVATION ANGLE GROUPING OF 4° TO 20° VERSUS 20° TO 30°

Mode S Azimuth Residuals (Deg)

		Elevation 4-20			Elevation 20-30		
Date (1980)	Test	No. Samples	Mean (deg)	Std Dev (deg)	No. Samples	Mean (deg)	Std Dev (deg)
7/1	19,000-ft radials	846	-0.021	0.038	84	-0.186	0.061
7/23	39,000-ft radials	532	0.037	0.032	89	-0.064	0.043

ATCRBS Azimuth Residuals (Deg)

		Elevation 4-20			Elevation 20-30		
Date (1980)	Test	No. Samples	Mean (deg)	Std Dev (deg)	No. Samples	Mean (deg)	Std Dev (deg)
7/1	19,000-ft radials	839	0.041	0.025	84	0.011	0.029
7/23	39,000-ft radials	522	0.058	0.025	89	0.030	0.030



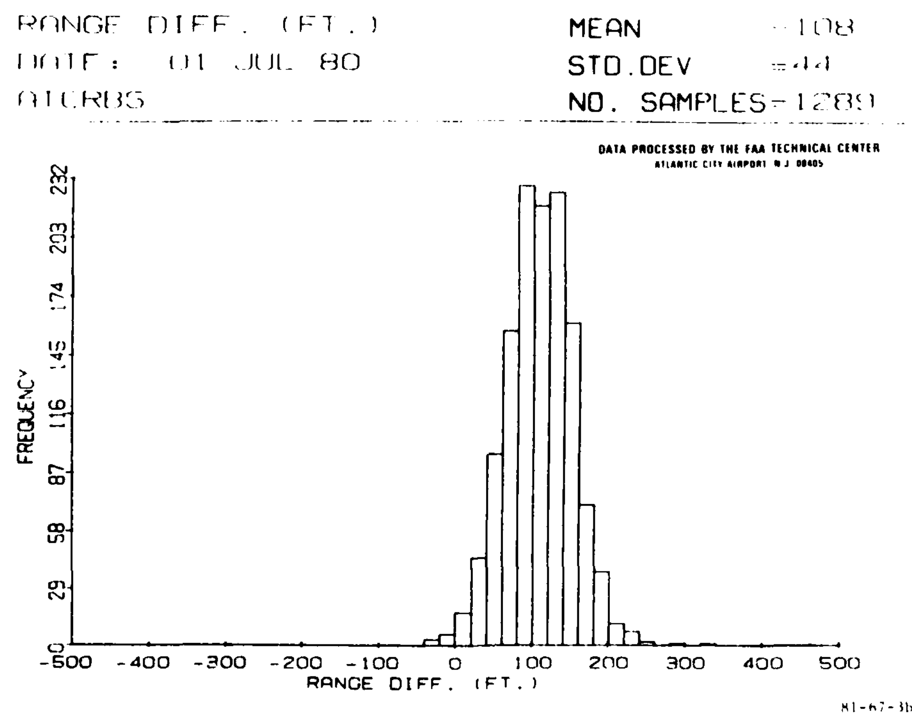
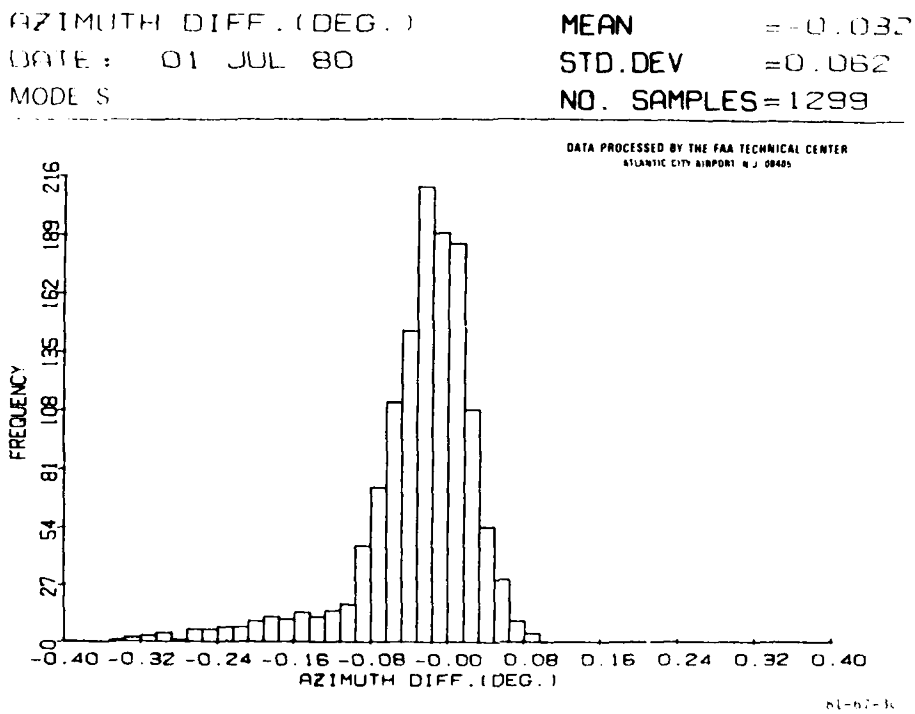


FIGURE 3. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR TECHNICAL CENTER SENSOR RADIAL FLIGHT OF JULY 1, 1980 (SHEET 1 OF 2)



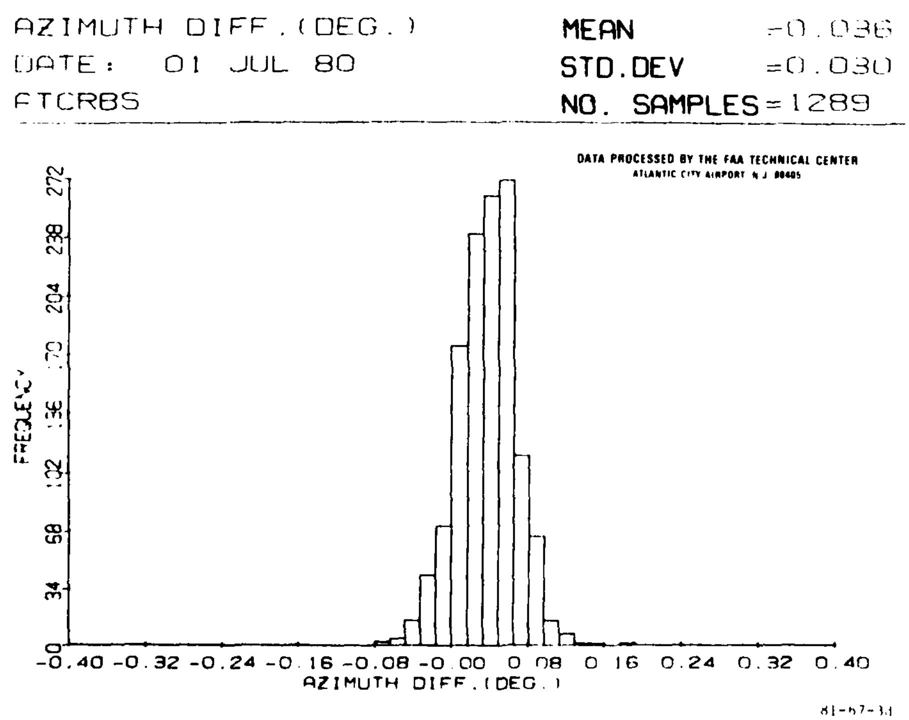
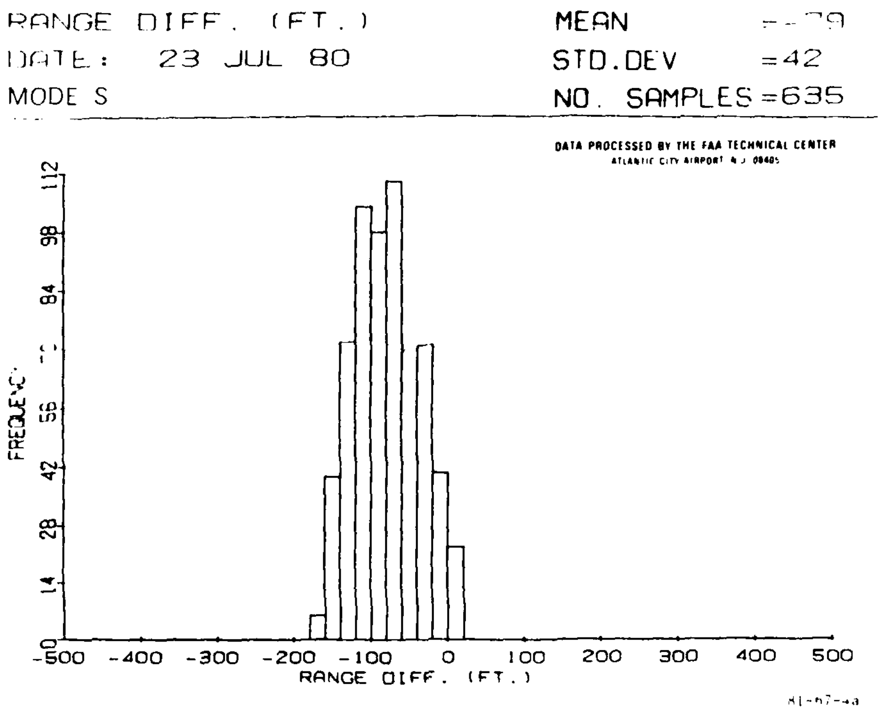


FIGURE 3. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR TECHNICAL CENTER SENSOR RADIAL FLIGHT OF JULY 1, 1980 (SHEET 2 OF 2)



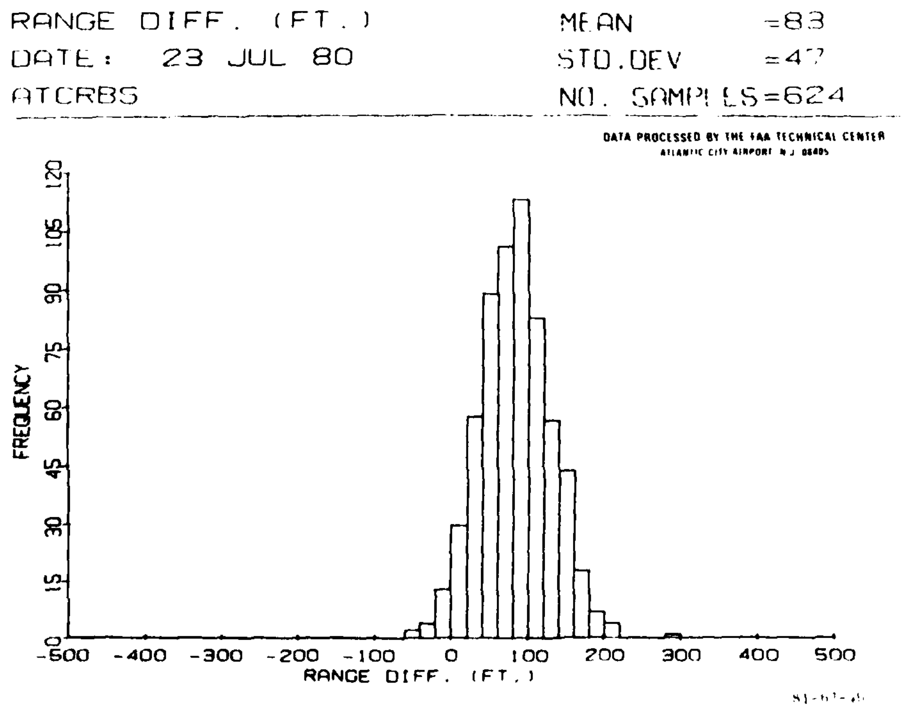
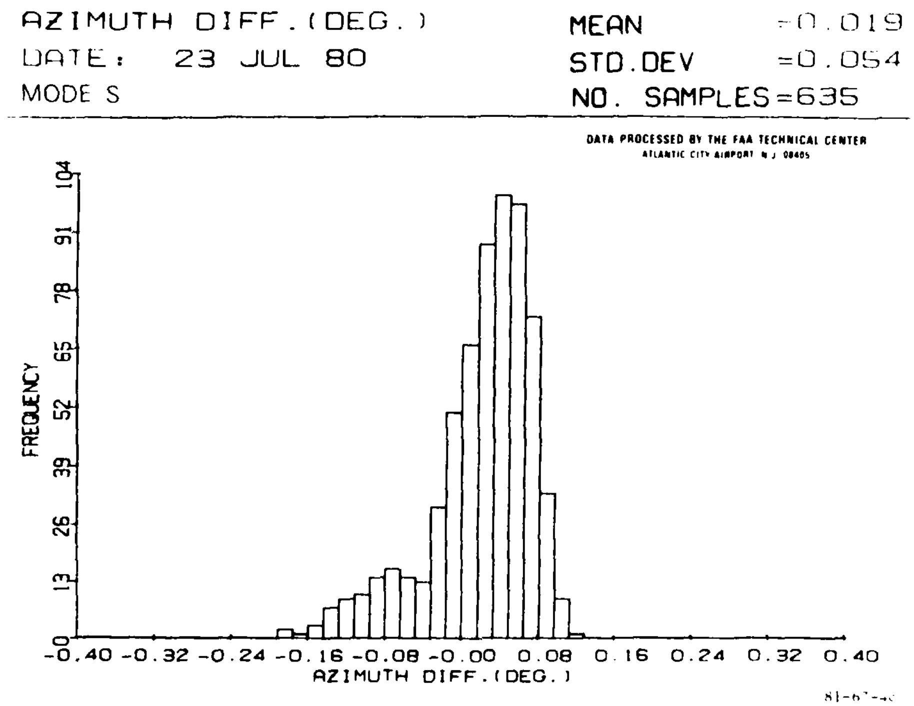


FIGURE 4. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR TECHNICAL CENTER SENSOR RADIAL FLIGHT OF JULY 23, 1980 (SHEET 1 OF 2)



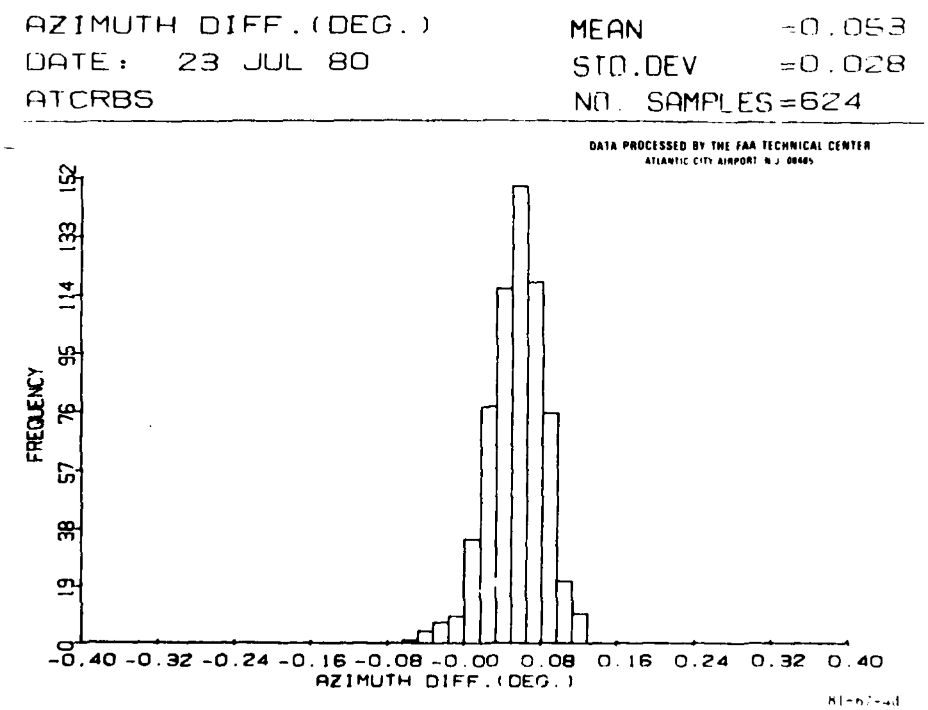
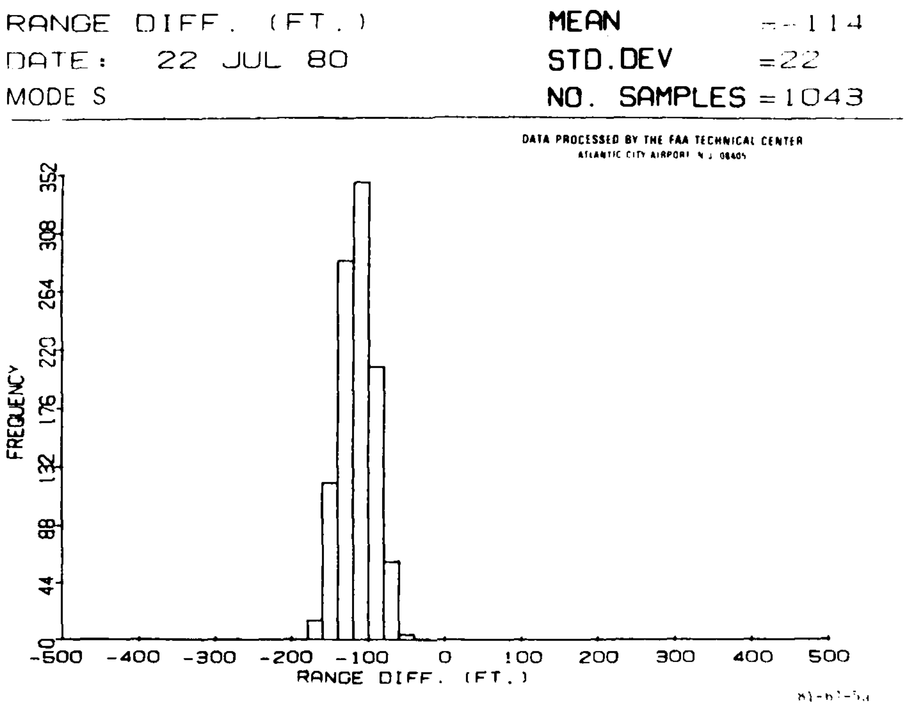


FIGURE 4. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR TECHNICAL CENTER SENSOR RADIAL FLIGHT OF JULY 23, 1980 (SHEET 2 OF 2)



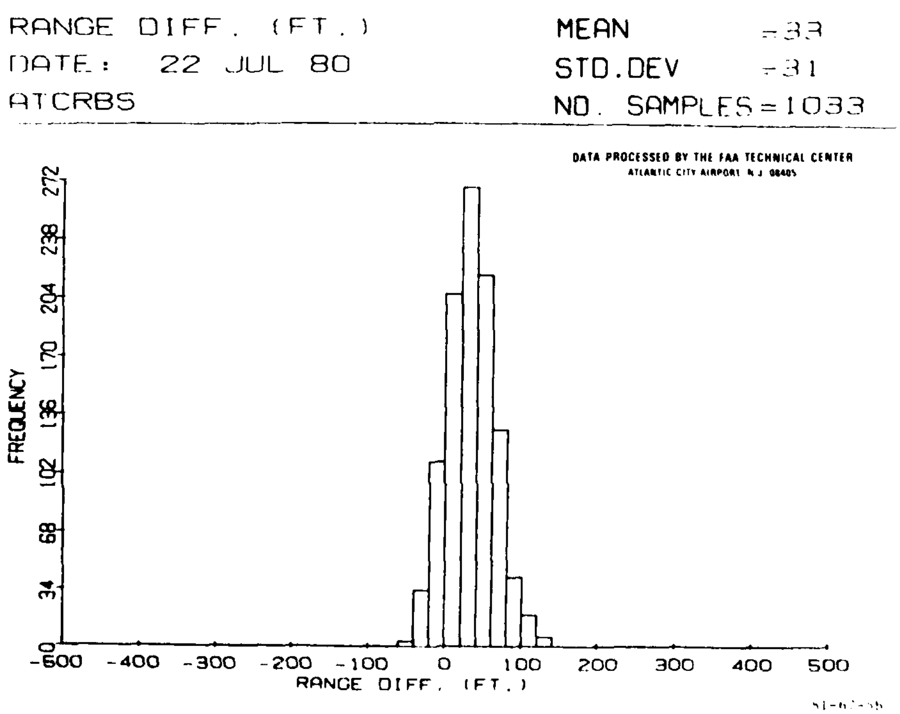
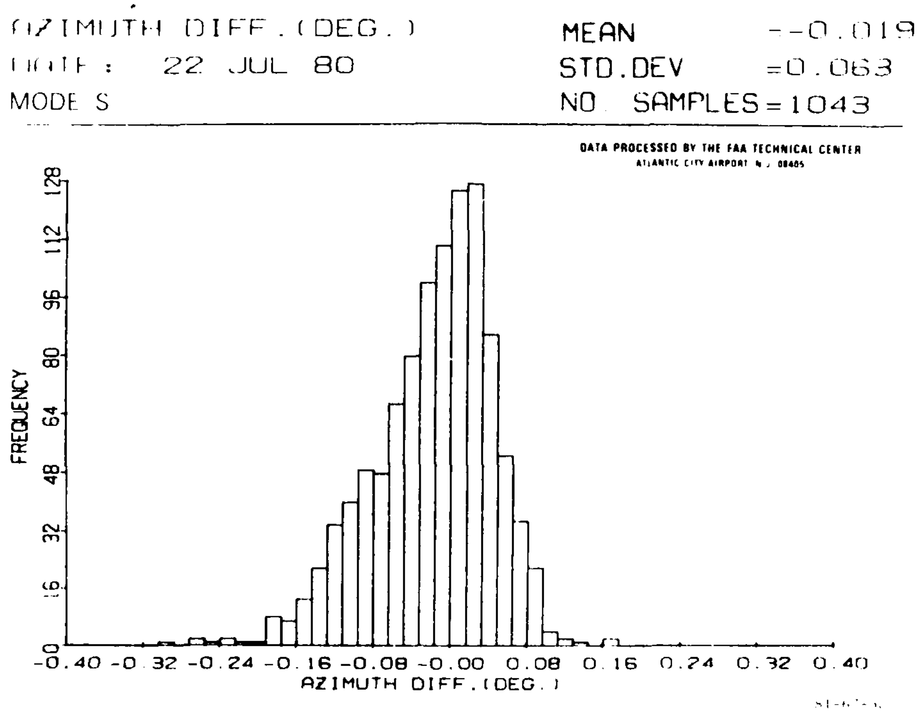


FIGURE 5. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR TECHNICAL CENTER SENSOR ORBITAL FLIGHTS OF JULY 22, 1980 (SHEET 1 OF 2)



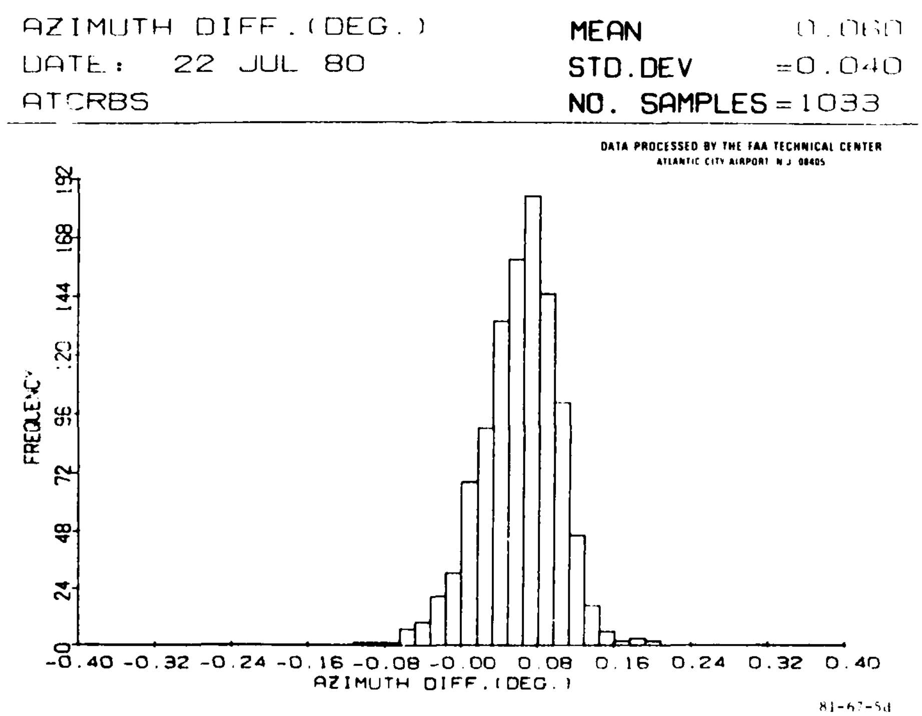
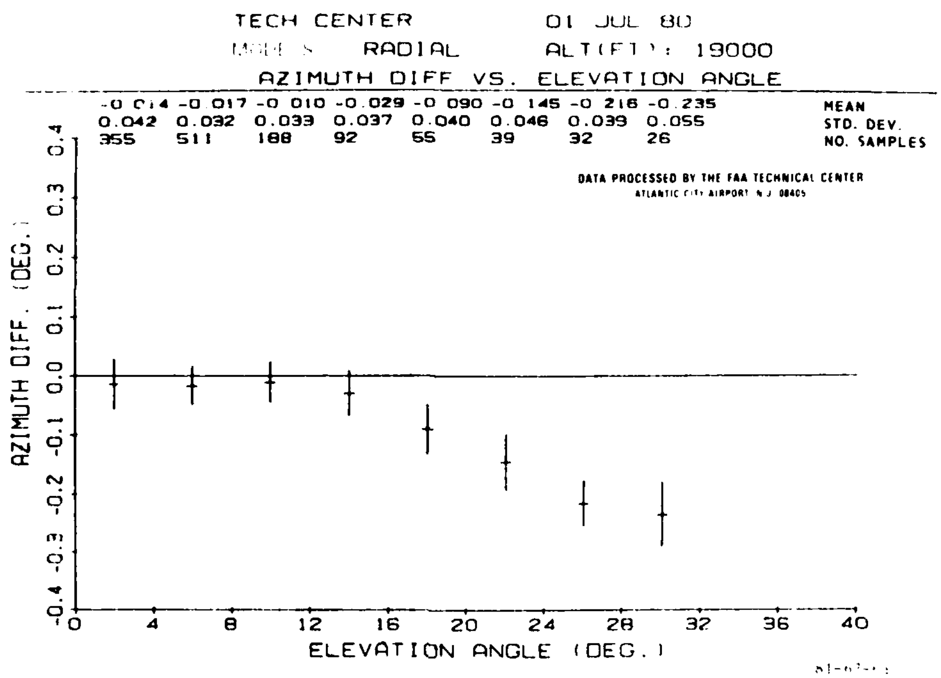


FIGURE 5. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR TECHNICAL CENTER SENSOR ORBITAL FLIGHTS OF JULY 22, 1980 (SHEET 2 OF 2)



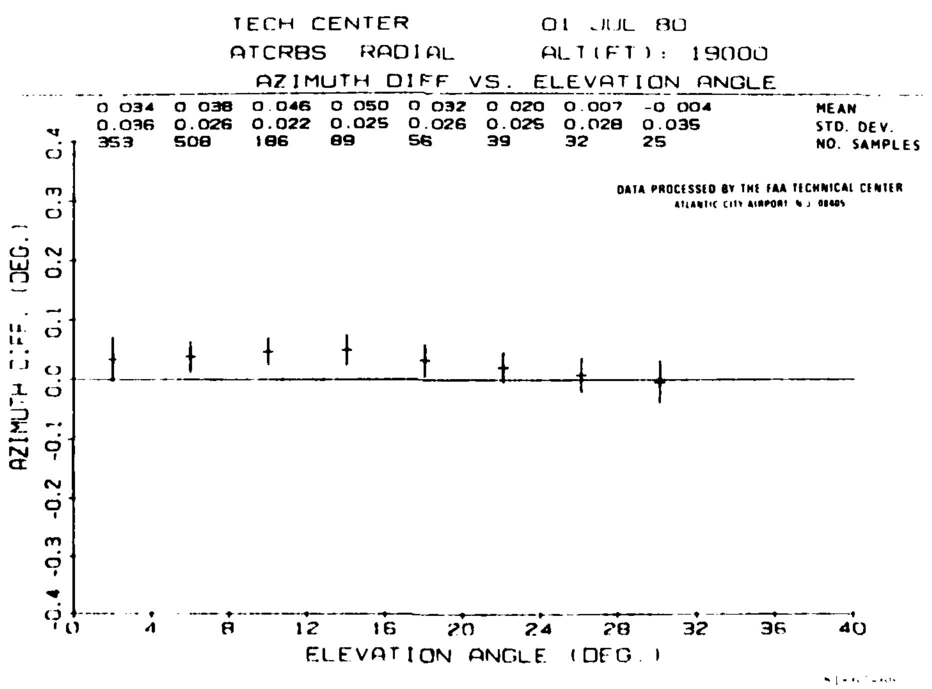
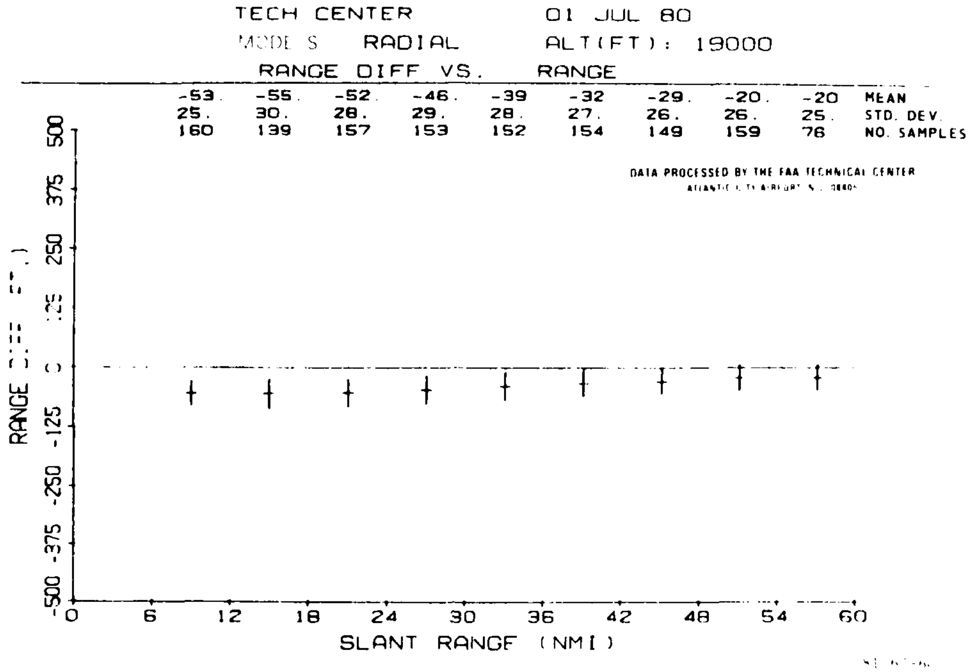


FIGURE 6. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR TECHNICAL CENTER RADIAL FLIGHTS OF JULY 1, 1980 (SHEET 1 OF 2)



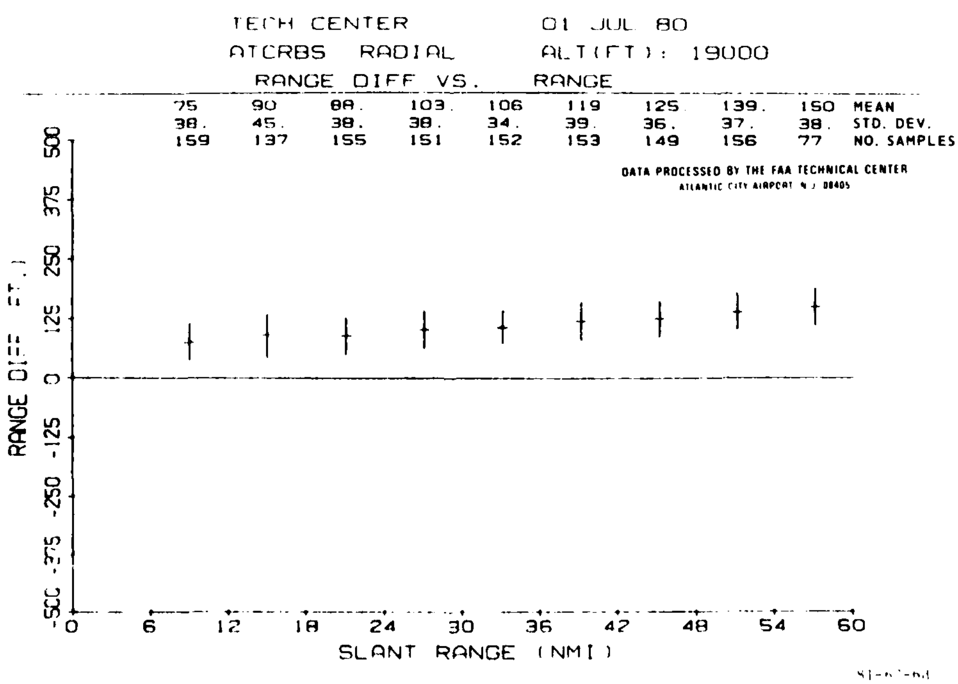
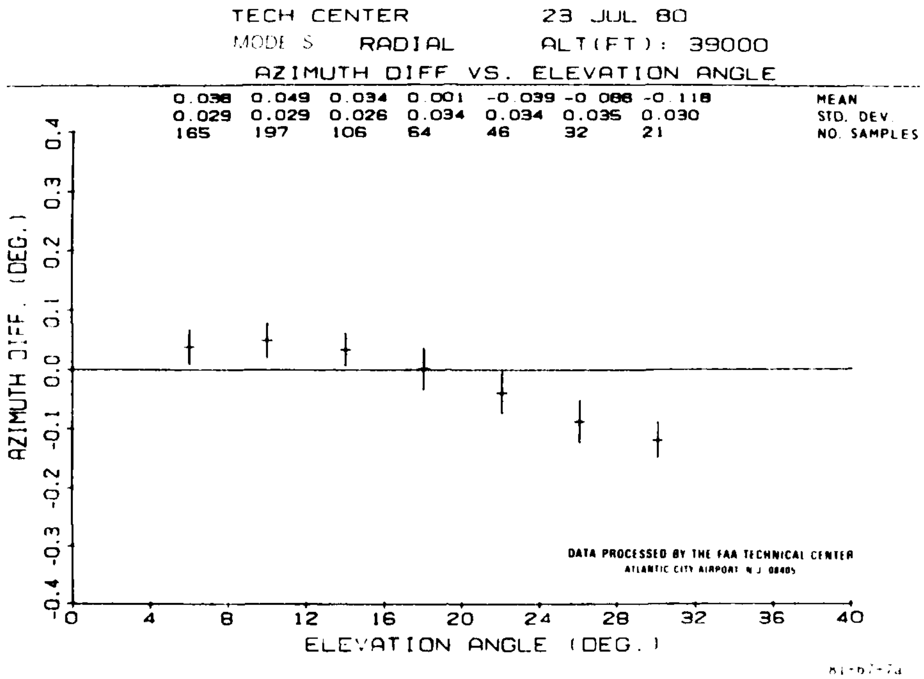


FIGURE 6. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR TECHNICAL CENTER RADIAL FLIGHTS OF JULY 1, 1980 (SHEET 2 OF 2)



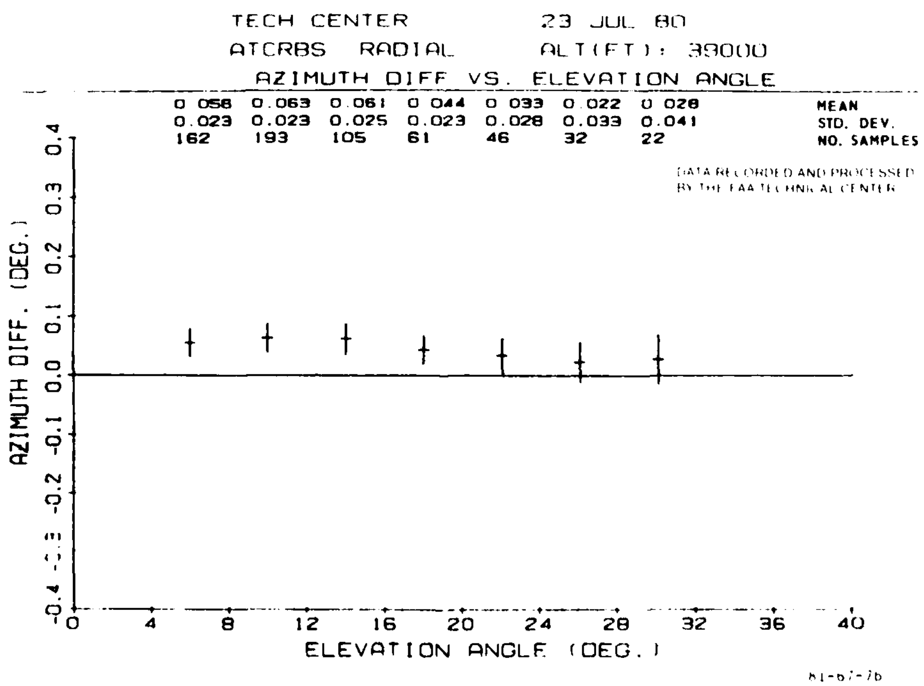
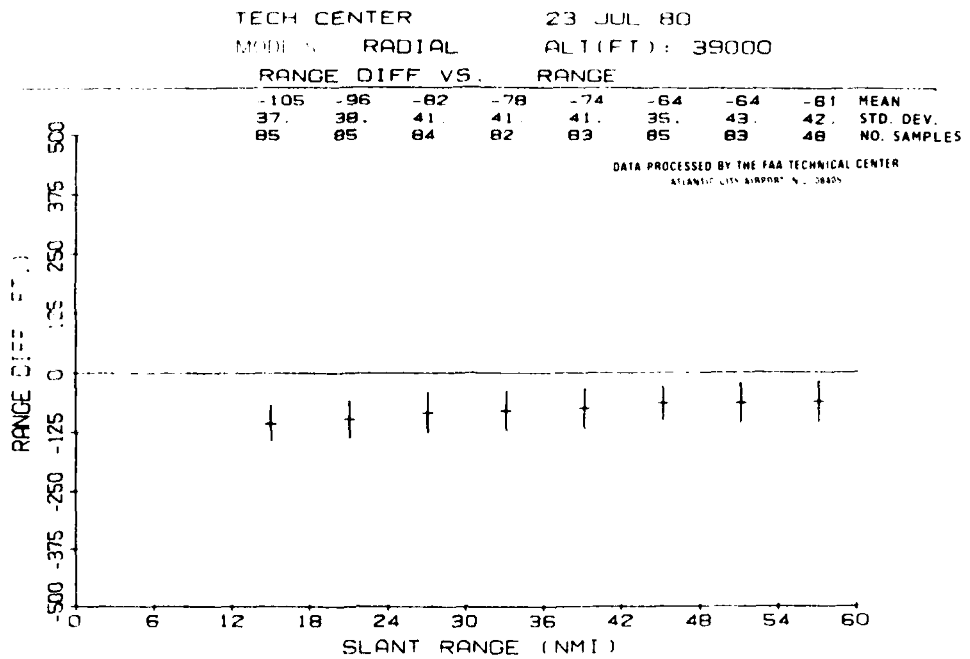


FIGURE 7. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR TECHNICAL CENTER RADIAL FLIGHTS OF JULY 23, 1980 (SHEET 1 OF 2)



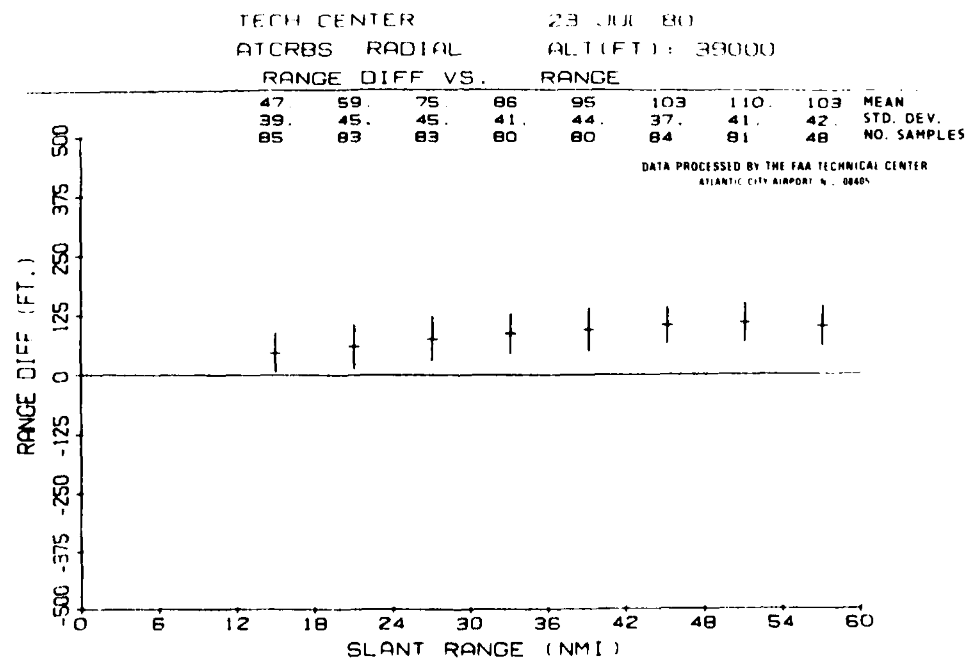
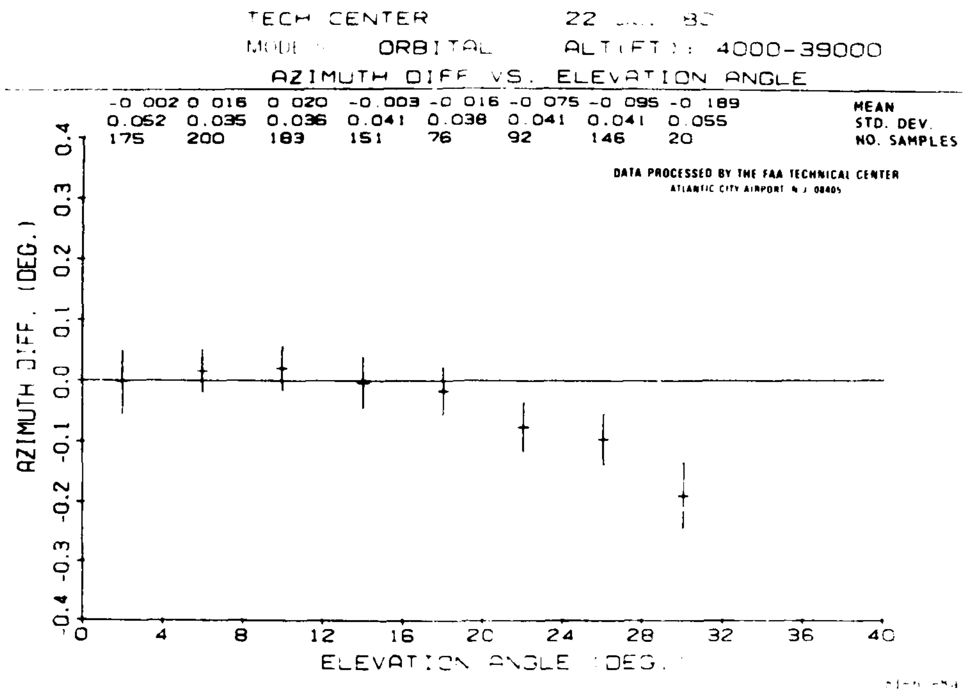


FIGURE 7. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR TECHNICAL CENTER RADIAL FLIGHTS OF JULY 23, 1980 (SHEET 2 OF 2)



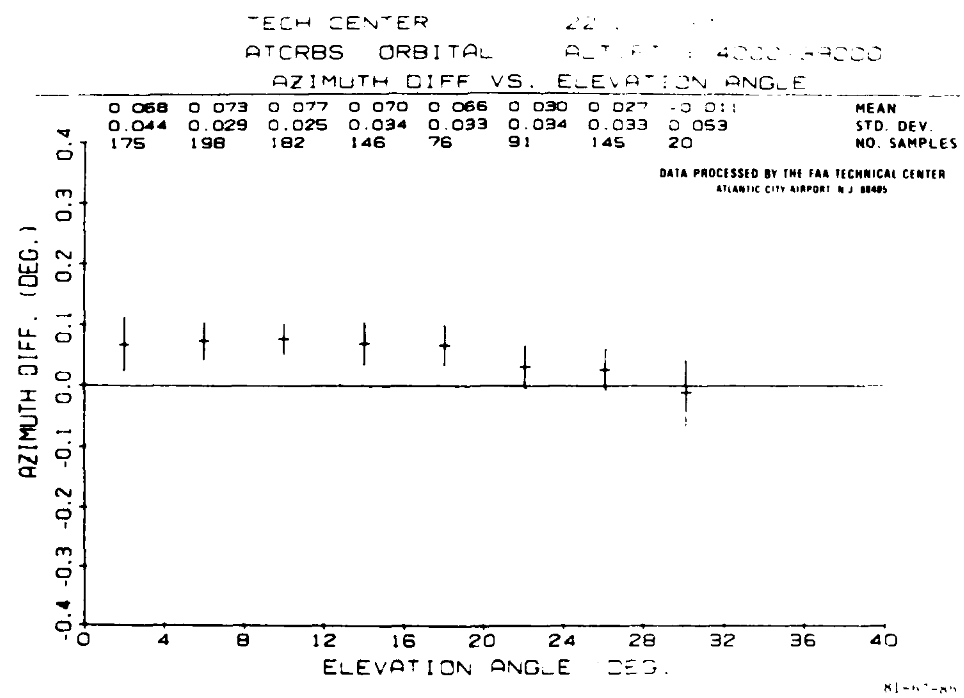
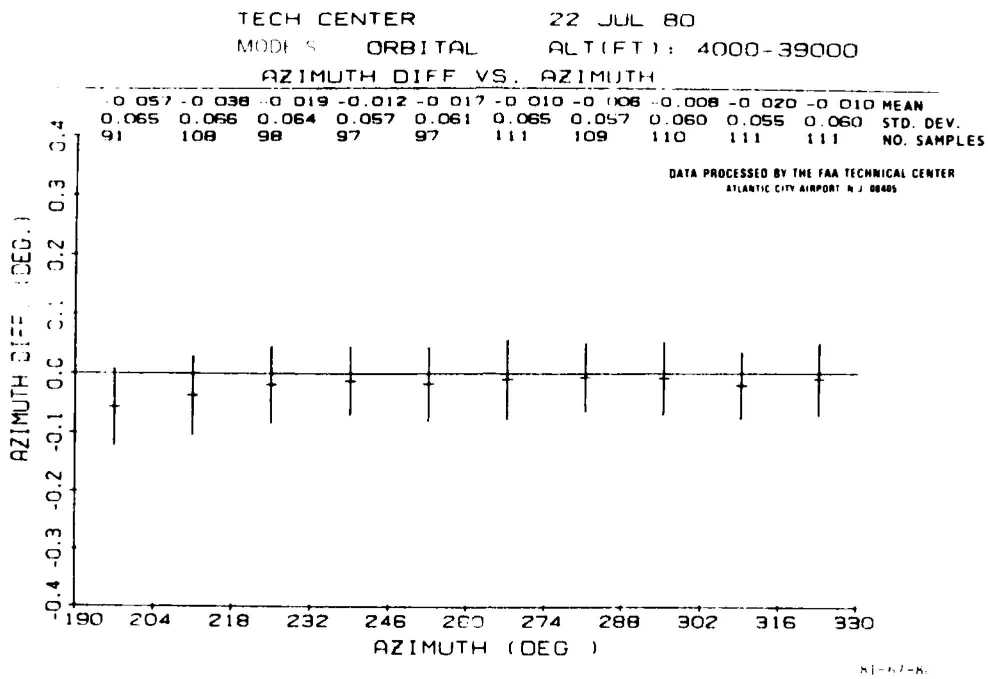


FIGURE 8. AZIMUTH RESIDUAL VERSUS ELEVATION AND AZIMUTH PLOTS FOR TECHNICAL CENTER ORBITAL FLIGHTS OF JULY 22, 1980 (SHEET 1 OF 2)



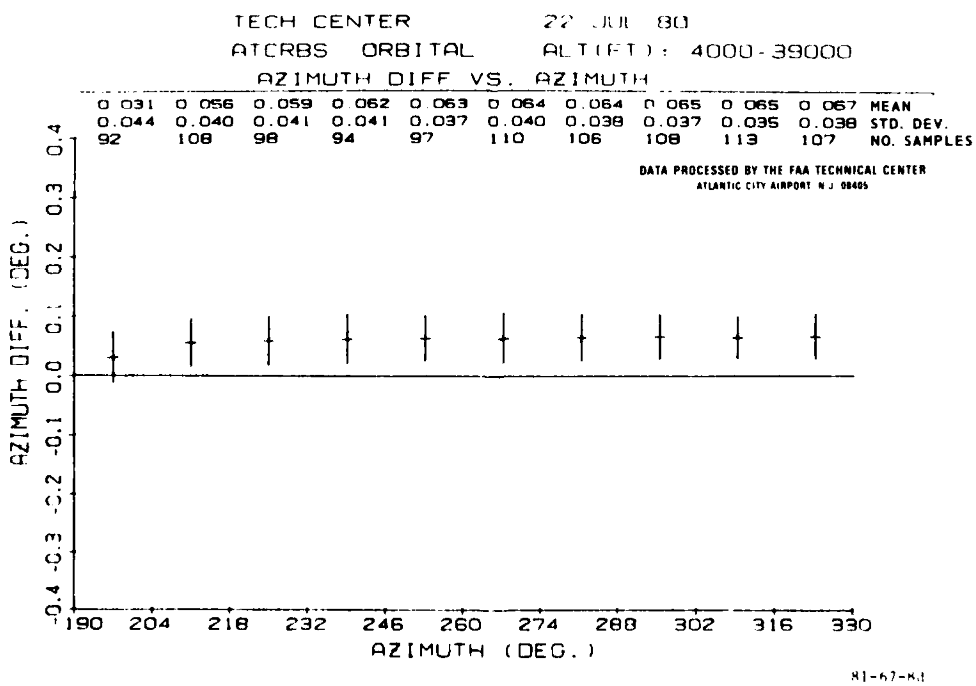


FIGURE 8. AZIMUTH RESIDUAL VERSUS ELEVATION AND AZIMUTH PLOTS FOR TECHNICAL CENTER ORBITAL FLIGHTS OF JULY 22, 1980 (SHEET 2 OF 2)

Empirical mathematical models were developed for azimuth residuals based on elevation angle and range residuals based on slant range.

The azimuth residual model is based on the secant of the elevation angle, as indicated on page 3-22 of the MITRE report (reference 2). The elevation angle affects the azimuth residual based on the widening of the antenna beam as the elevation angle increases.

Table 5 tabulates the results of the azimuth regression model for the three test dates at the Technical Center sensor. The model coefficients showed the same general trend for all three test dates with the azimuth residuals degrading at the higher elevation angles. The secant coefficient showed the same general trend for all three test dates with the azimuth residuals degrading at the higher elevation angles. The secant coefficient ranged between -1.16 to -1.59 for Mode S, with the higher absolute coefficient indicating a steeper slope or effect due to elevation angle. For each set of data, the A_0 and A_1 coefficients were close in magnitude and opposite in sign resulting in azimuth residuals near zero at low elevations. For Mode S, the elevation angle effect is noticeable at about 10° with significant changes occurring at elevations exceeding 20°. Figure 9 illustrates this effect by plotting the regression model curve superimposed on the Mode S azimuth residual mean/standard deviation data for the July 1 radial flights. By way of contrast, the ATCRBS secant model coefficients were much less than Mode S and the model and data show only a moderate slope at high elevation. The difference in the secant coefficients between Mode S and ATCRBS is due to the fact that Mode S uses one reply per scan near the leading edge of the beam, and ATCRBS averages the two replies nearest the borésight.

The model illustrated in figure 9 reduced a raw standard deviation of 0.062° down to a standard error of 0.038°. The 39,000-foot radial flights at the Technical Center had a similar effect, decreasing a 0.054° raw data standard deviation to a 0.0305° standard error using the model. Using the ATCRBS azimuth model, the standard error (0.029°) was about 3 percent less than raw standard deviation of 0.030°.

The slant range residuals are modeled based on slant range. The units used in the model are feet for the range residuals and nautical miles for the slant range. All four radial test dates were used. The Mode S and ATCRBS model coefficients are contained in table 5.

Plots of the 19,000-foot Technical Center sensor radial flight data are plotted for Mode S and ATCRBS data in figure 10. The linear regression model equation is plotted along with the mean data, plus and minus one standard deviation. Although the Mode S range model slope in the figure 10 test was 0.83, based on one test date, the model slope was 1.10 for the other Technical Center radial test date, indicating that the range residuals shift about 1-foot per nmi. The raw Mode S data standard deviation of 30 feet in figure 10 was reduced to a 27-foot standard error using the model, representing about a 10 percent reduction.

The ATCRBS slope of figure 10 was 1.48 based on one day of testing at the Technical Center. A second full day of radial test flights at the Technical Center sensor showed a slope of 1.57. Since the Technical Center tests encompass the largest spread of slant ranges, these tests are the most appropriate to use in determining the slope. Based on the two test dates, this model slope for the ATCRBS data

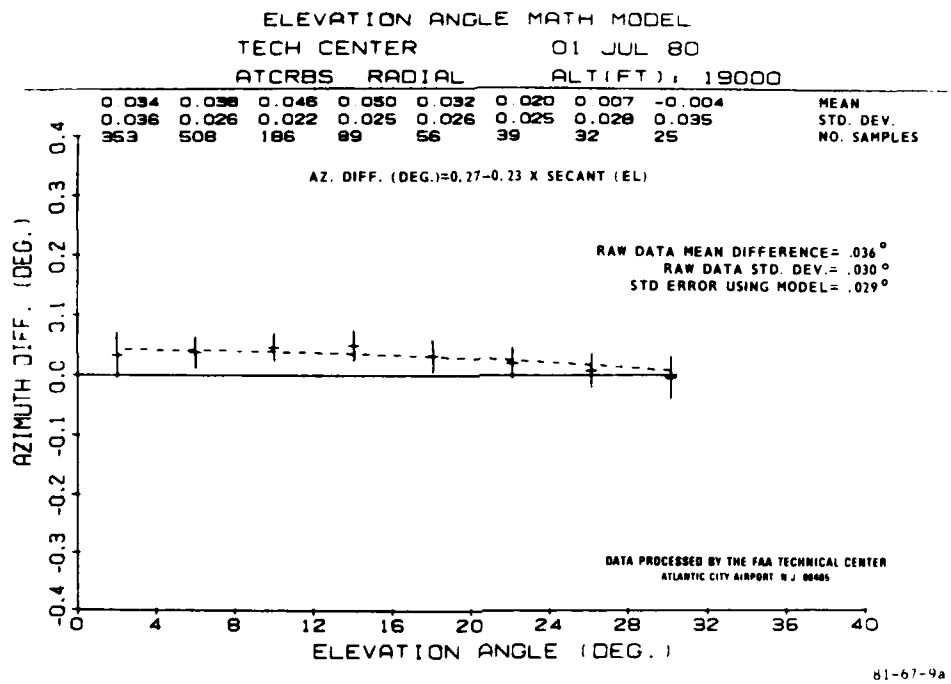
TABLE 5. MATHEMATICAL REGRESSION MODELS OF AZIMUTH AND RANGE RESIDUALS

Azimuth Residuals = $A_0 + A_1 \times$ Secant (Elevation Angle)

			Mode S			ATCRBS		
Sensor	Type of Flight	Date (1980)	No. Samples	A_0	A_1	No. Samples	A_0	A_1
Tech Center	19,000-ft radials	7/1	1,299	1.58	-1.59	1,289	0.27	-0.23
Tech Center	39,000-ft radials	7/23	635	1.22	-1.17	634	0.37	-0.31
Tech Center	Orbitals	7/22	1,043	1.18	-1.16	1,033	0.58	-0.50

Range Residuals (ft) = $A_0 + A_1 \times$ Slant Range (nmi)

			Mode S			ATCRBS		
Sensor	Type of Flight	Date (1980)	No. Samples	A_0	A_1	No. Samples	A_0	A_1
Tech Center	19,000-ft radials	7/1	1,299	-66	0.83	1,289	61	1.48
Tech Center	39,000-ft radials	7/23	635	-117	1.10	634	29	1.57
Clementon	Radials	7/24	481	-66	0.68	454	78	0.93



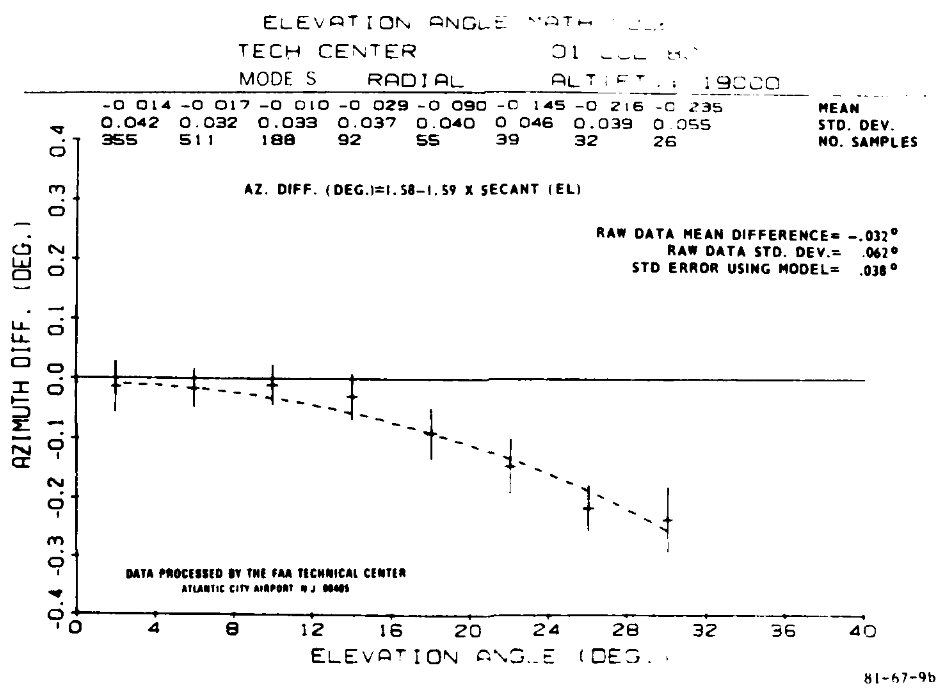
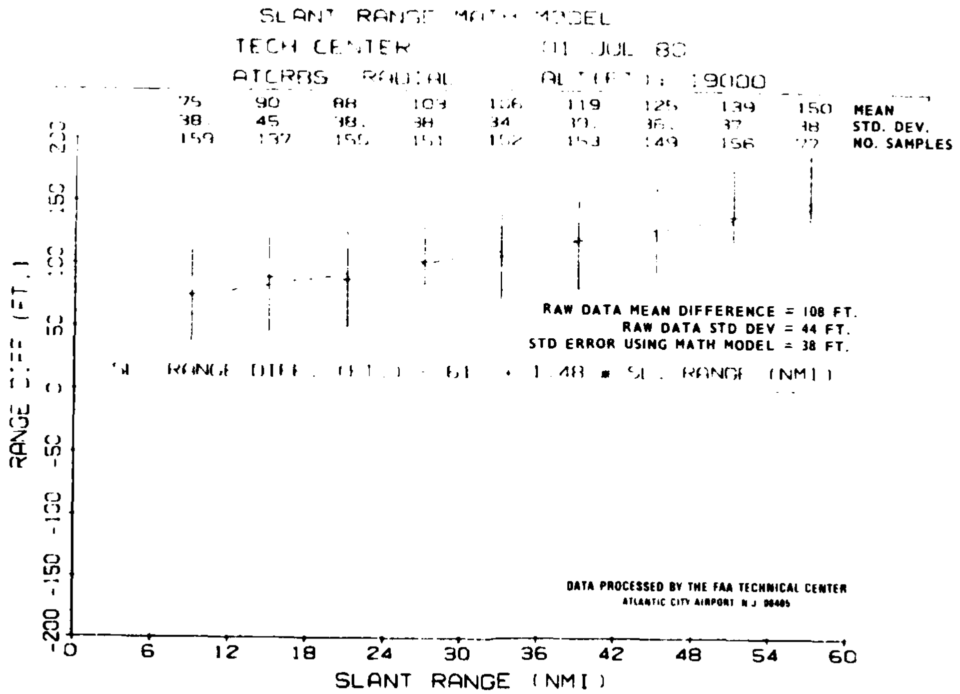
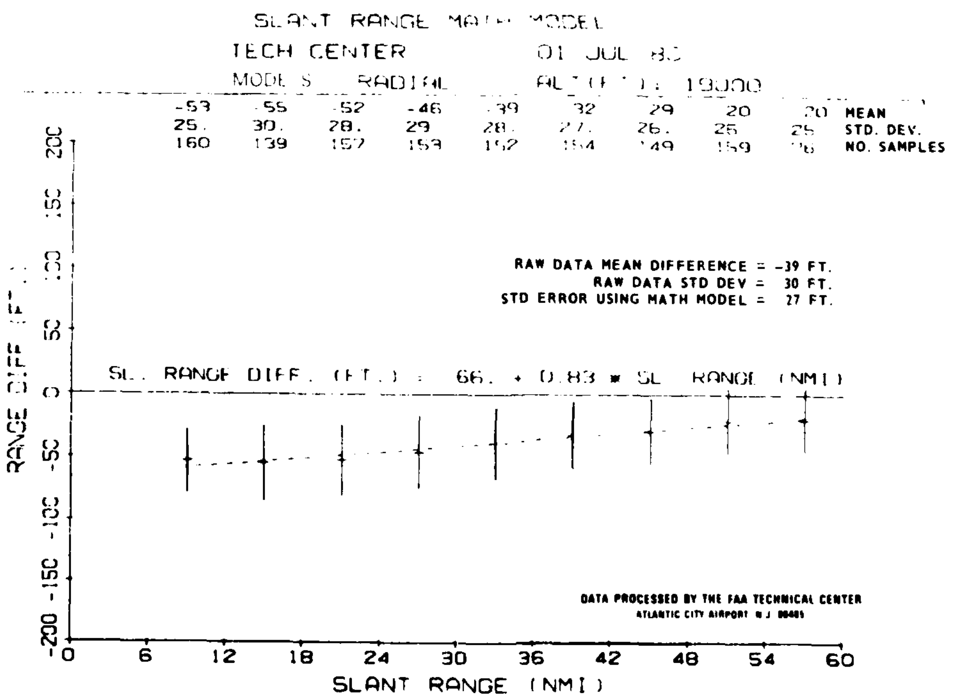


FIGURE 9. AZIMUTH RESIDUAL MATHEMATICAL MODEL PLOTS



81-67-10a



81-67-10b

FIGURE 10. RANGE RESIDUAL MATHEMATICAL MODEL PLOTS

approximates 1.5-foot change in range residual per nmi. The ATCRBS model slope is approximately 0.5 greater than the Mode S model slope since the ATCRBS transponder delay changes considerably based on power setting. The raw ATCRBS standard deviation of 44 feet was reduced to a 38-foot standard error using the model, which represents a 14 percent reduction.

CLEMENTON SENSOR.

Data processed from the Clementon Mode S sensor consisted of radial flights flown at altitudes of 13,000, 26,000, and 39,000 feet, and orbital flights from 120° to 148° azimuth, relative to the sensor at altitudes ranging from 7,000 to 37,000 feet. The radial flights were flown from approximately 30 to 55 nmi from the sensor providing elevation angle data from approximately 3° to 12°. The summary of the azimuth and range residuals for the 2 days of testing is contained in table 6. The Mode S and ATCRBS mean azimuth position relative to the tracker position was within 0.06° for both tests. The Mode S azimuth residual standard deviations of 0.026° and 0.032° were about half of what was observed at the Technical Center sensor due, primarily, to the fact that the largest elevation angle processed at Clementon was about 12°.

TABLE 6. CLEMENTON SENSOR AZIMUTH AND SLANT RANGE RESIDUALS

Azimuth Residuals (deg)

			Mode S			ATCRBS		
Date (1980)	Test Flights	No. Flights	No. Samples	Mean (deg)	Std Dev (deg)	No. Samples	Mean (deg)	Std Dev (deg)
7/24	Radials	9	481	-0.040	0.026	455	-0.060	0.021
7/10	Orbital/Arcs	24	800	0.019	0.032	797	-0.020	0.032

Slant Range Residuals (ft)

			Mode S			ATCRBS		
Date (1980)	Test Flights	No. Flights	No. Samples	Mean (ft)	Std Dev (ft)	No. Samples	Mean (ft)	Std Dev (ft)
7/24	Radials	9	481	-38	28	455	117	31
7/10	Orbital/Arcs	24	800	27	22	797	179	33

Figures 11 and 12 contain Mode S and ATCRBS azimuth and range residual histograms. The Mode S azimuth residuals do not show the skewness that appeared at the Technical Center since no high elevation data were processed at Clementon. The problem with processing high elevation data at Clementon is that the Nike tracker error becomes unacceptable when the aircraft is close to the Clementon sensor. This large tracker azimuth error is a result of the geometric translations of tracker data to the Mode S site. Hence, all flights were conducted such that the aircraft was closer to the tracker than to the sensor. The histogram plots illustrate the data distribution and define the extreme values.

Figure 13 provides the azimuth residuals plotted against the elevation angle and range residuals plotted versus slant range for the radial flights. The orbital flight plots of figure 14 comprise azimuth residuals plotted against both azimuth angle and elevation angle for the Mode S and ATCRBS data.

OVERALL AVERAGE RESIDUALS.

The overall average azimuth residuals for elevation angles below 12.5° at the Technical Center and Clementon sensors were 0.001° and 0.018° for Mode S and ATCRBS reports. The Mode S and ATCRBS standard deviations for these data were 0.042° and 0.054°, respectively, and are based on over 3,200 data samples each. These deviations, based on all five test dates, substantially exceed the individual standard deviations associated with each test because of mean residual differences among the five tests.

The grand overall average slant range residuals for elevation angles below 12.5° at the Technical Center and Clementon sensors were -39 and 114 feet for Mode S and ATCRBS reports, respectively. The standard deviation was 55 feet for the Mode S reports and 61 feet for the ATCRBS reports. These deviations for the sum of the data from the five test dates were considerably greater than the individual deviations for each test for the same reason as with the azimuth data.

The overall average azimuth residuals for all elevation angles processed at the Technical Center and Clementon sensors were -0.013° and 0.023° for Mode S and ATCRBS reports with respective standard deviations of 0.059° and 0.051° based on about 4,200 samples of data.

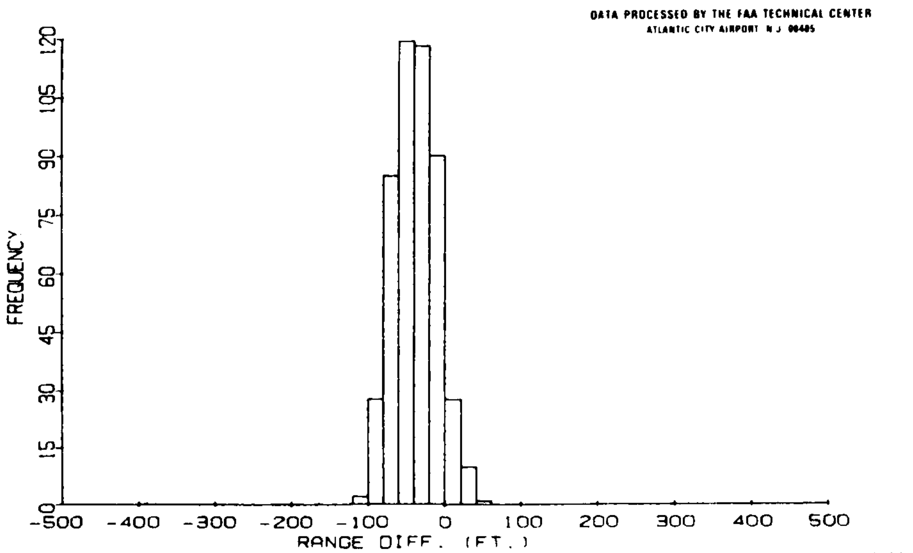
The overall mean range residual for all elevation angles at the two sensors was -51 feet with a standard deviation of 56 feet for Mode S. For ATCRBS data, the overall mean range residual was 100 feet with a 62-foot standard deviation for all elevation angles at the two sensors. As stated previously, all deviations for the sum of the data from the five tests exceed the individual deviations of each test.

COMMON SENSOR PROBLEMS. The test data indicated the existence of two problems common to both sensors. The first problem consisted of an azimuth long and short term drift caused by the sensor. The second problem is the large ATCRBS range bias of about 150 feet greater than the Mode S range bias. This problem is attributed to faulty transponder delay measurements (appendix C).

1. Azimuth Long and Short Term Drift. The azimuth residual data contained a short and long term drift attributed to the Mode S sensor. This determination was made by investigating the data from each test flight and examining the change in

RANGE DIFF. (FT.)
DATE: 24 JUL 80
MODE S

MEAN =-38
STD.DEV =28
NO. SAMPLES=481



RANGE DIFF. (FT.)
DATE: 24 JUL 80
ATCRBS

MEAN =117
STD.DEV =32
NO. SAMPLES=455

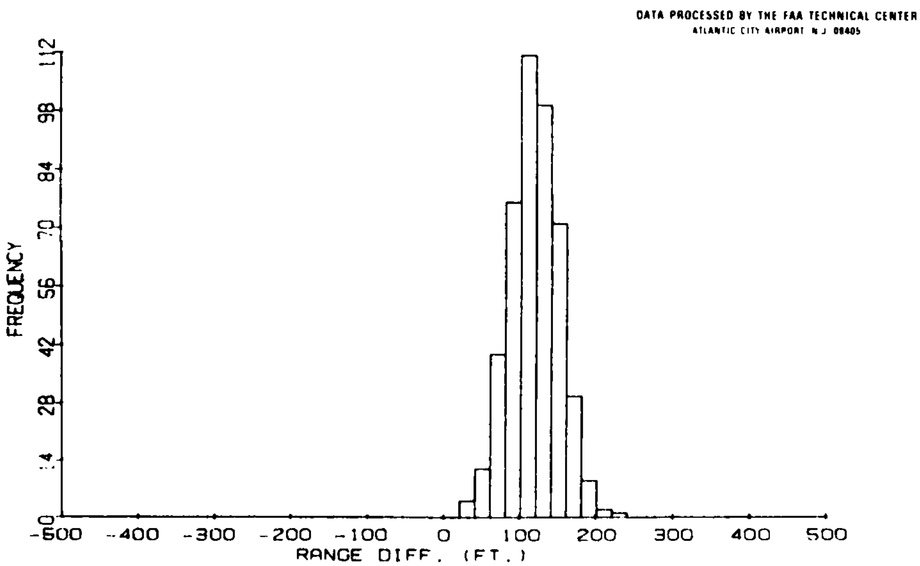
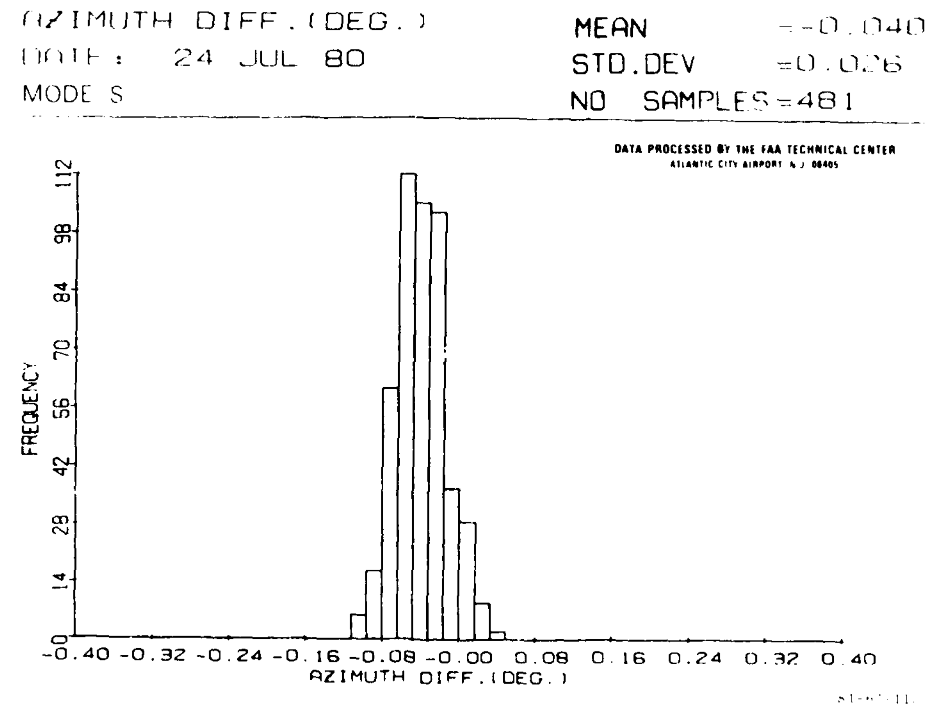


FIGURE 11. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR CLEMENTON SENSOR RADIAL FLIGHTS OF JULY 24, 1980 (SHEET 1 OF 2)



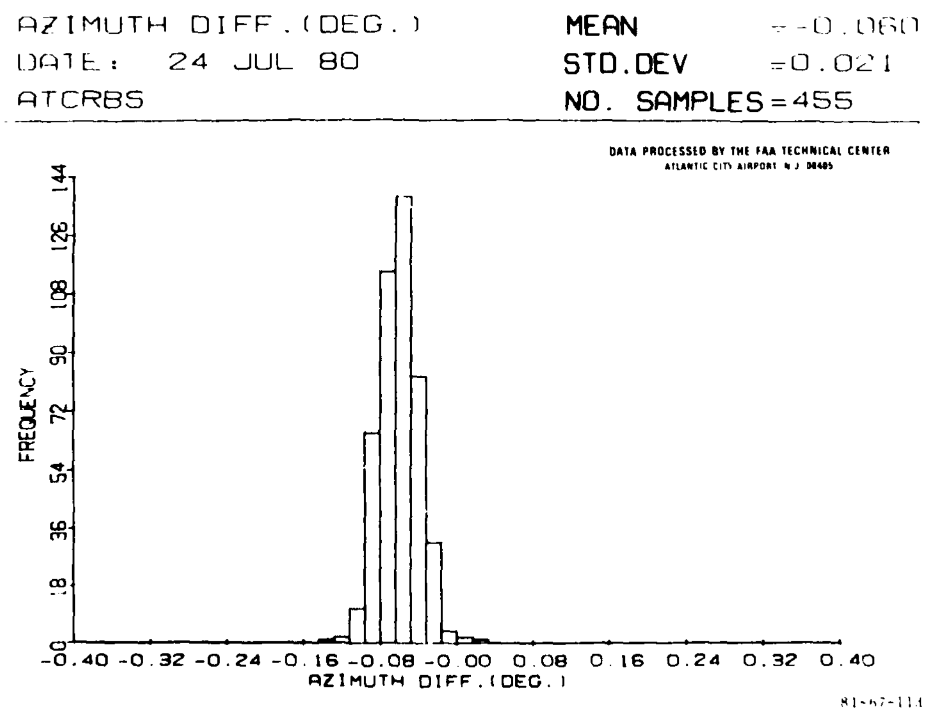
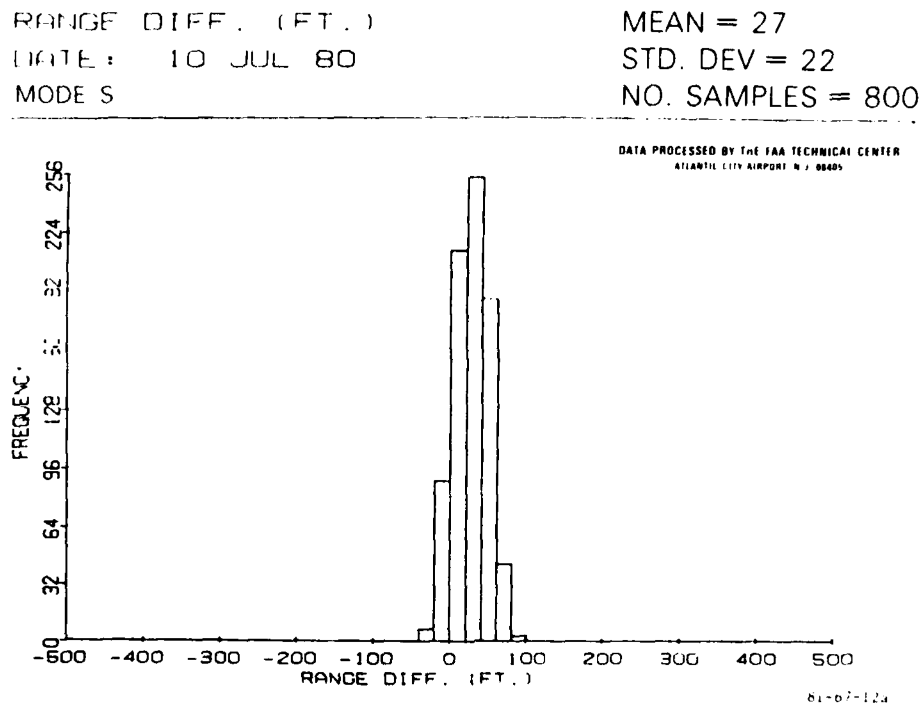


FIGURE 11. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR CLEMENTON SENSOR RADIAL FLIGHTS OF JULY 24, 1980 (SHEET 2 OF 2)



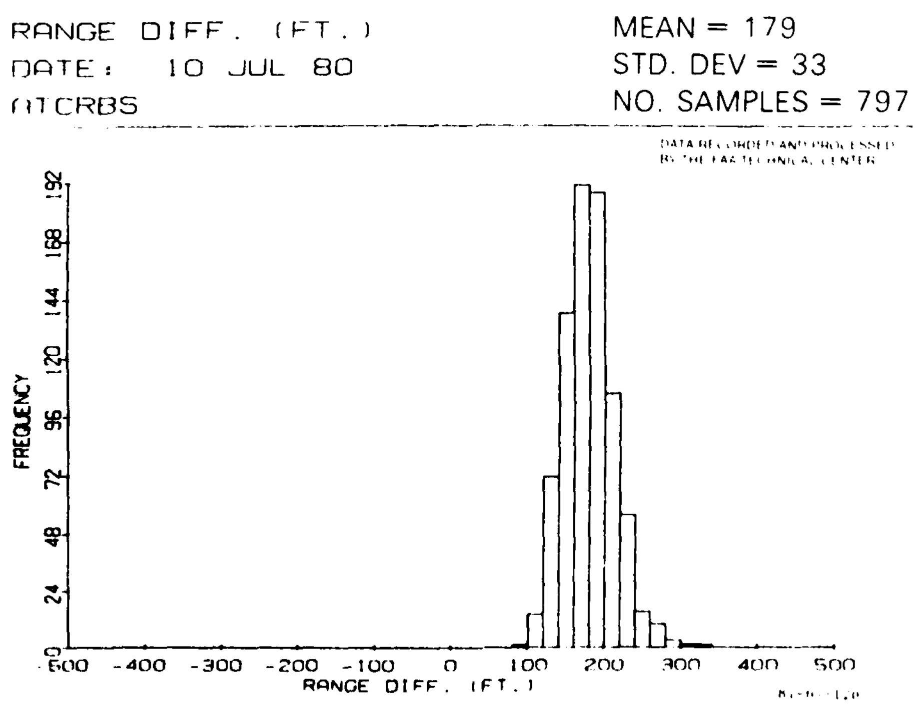
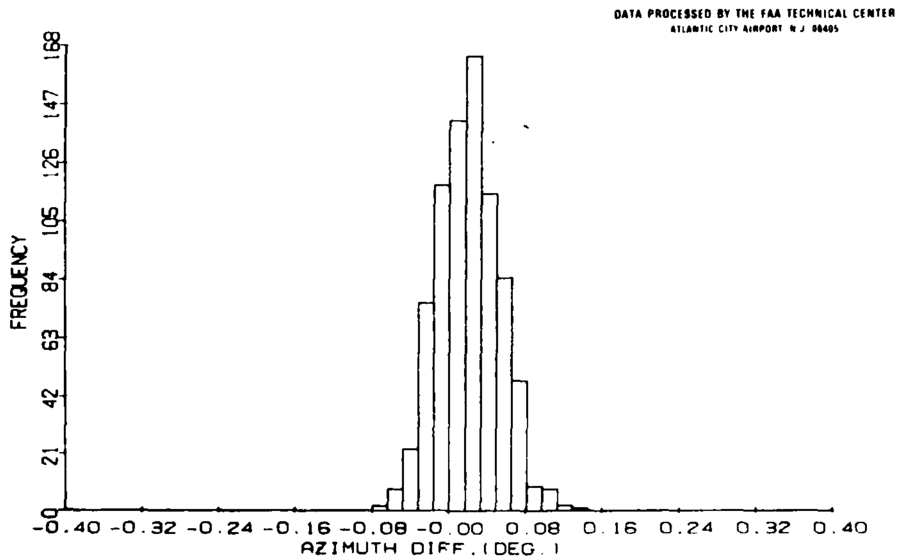


FIGURE 12. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR CLEMENTON SENSOR ORBITAL FLIGHTS OF JULY 10, 1980 (SHEET 1 OF 2)

AZIMUTH DIFF.(DEG.) MEAN =0.019
DATE: 10 JUL 80 STD.DEV =0.032
MODE S NO. SAMPLES=800



AZIMUTH DIFF.(DEG.) MEAN =-0.020
DATE: 10 JUL 80 STD.DEV =0.032
ATCRBS NO. SAMPLES=797

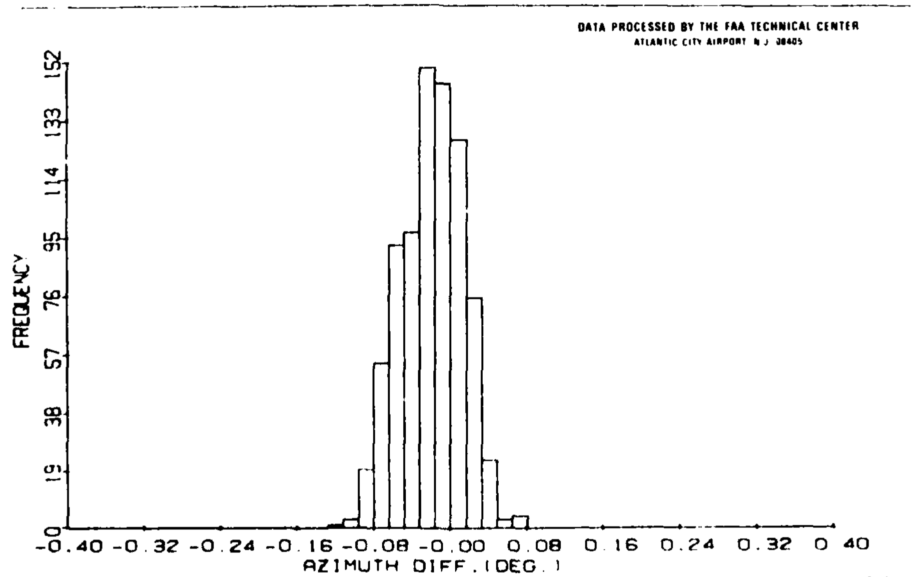
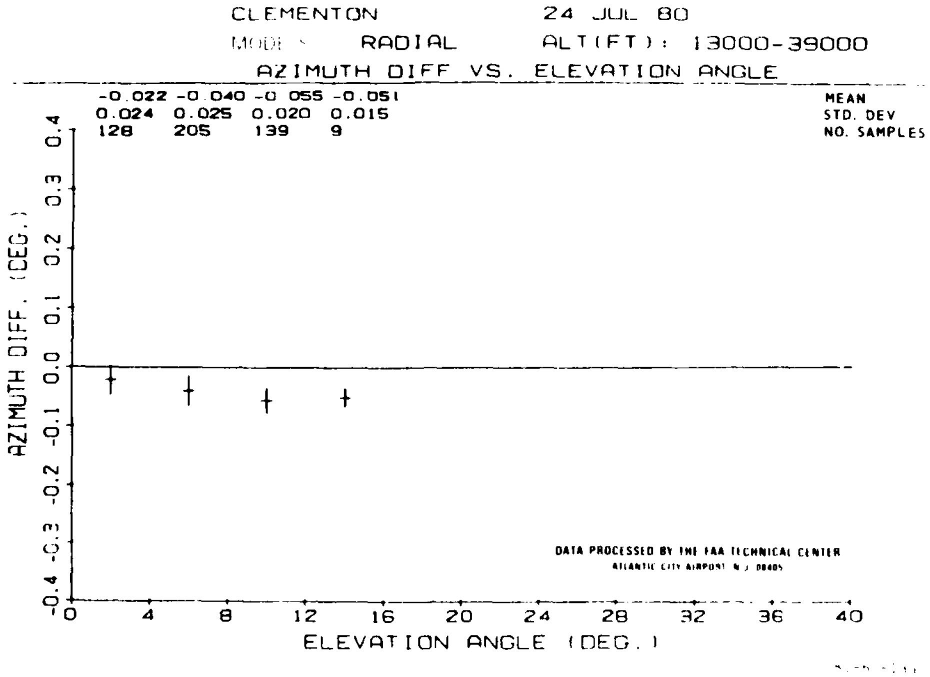


FIGURE 12. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR CLEMENTON SENSOR ORBITAL FLIGHTS OF JULY 10, 1980 (SHEET 2 OF 2)



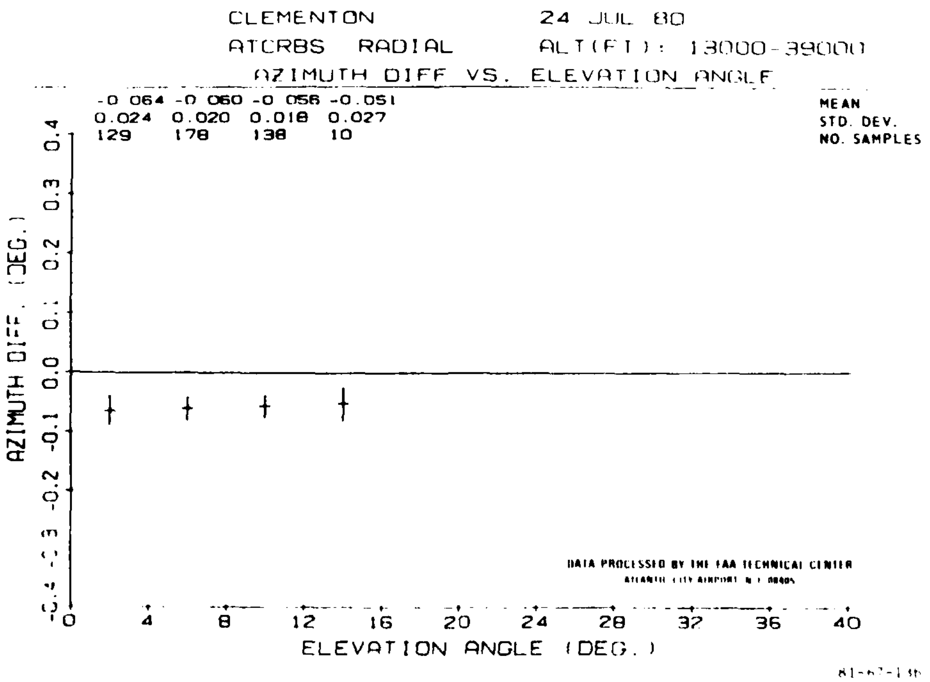
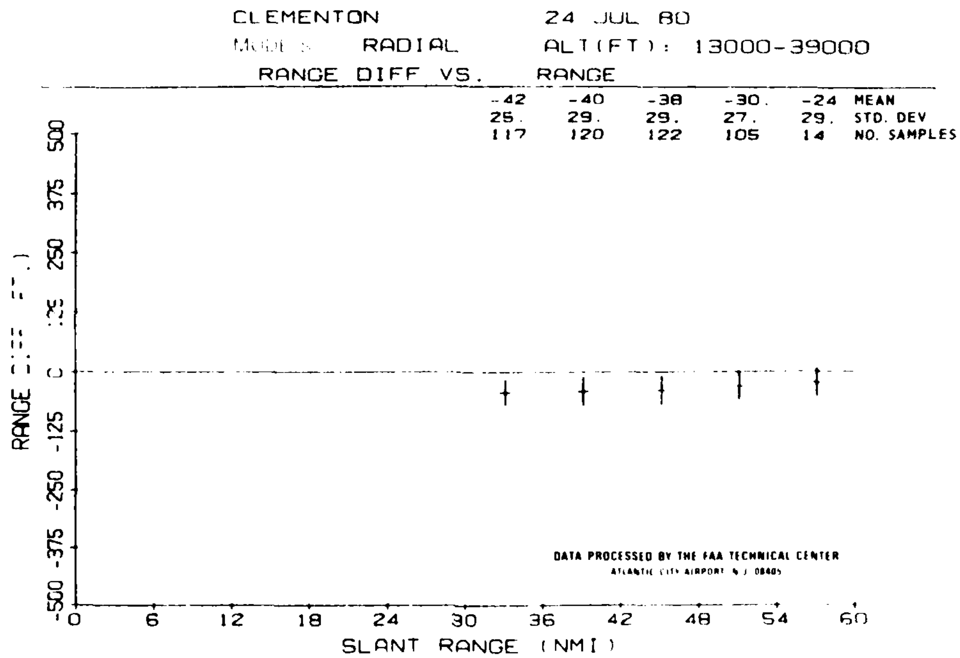


FIGURE 13. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR CLEMENTON RADIAL FLIGHTS OF JULY 24, 1980 (SHEET 1 OF 2)



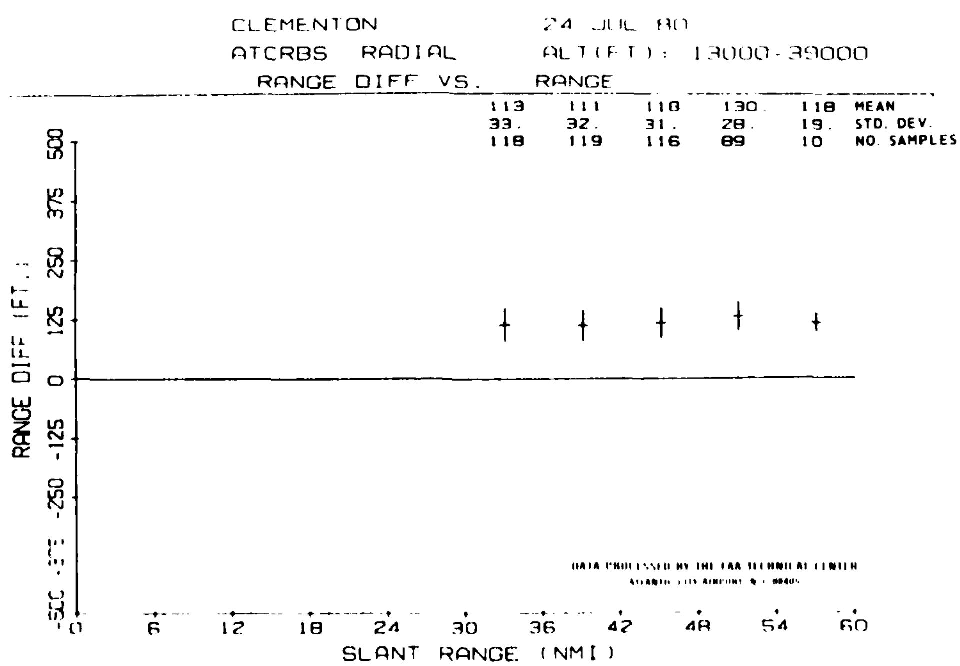
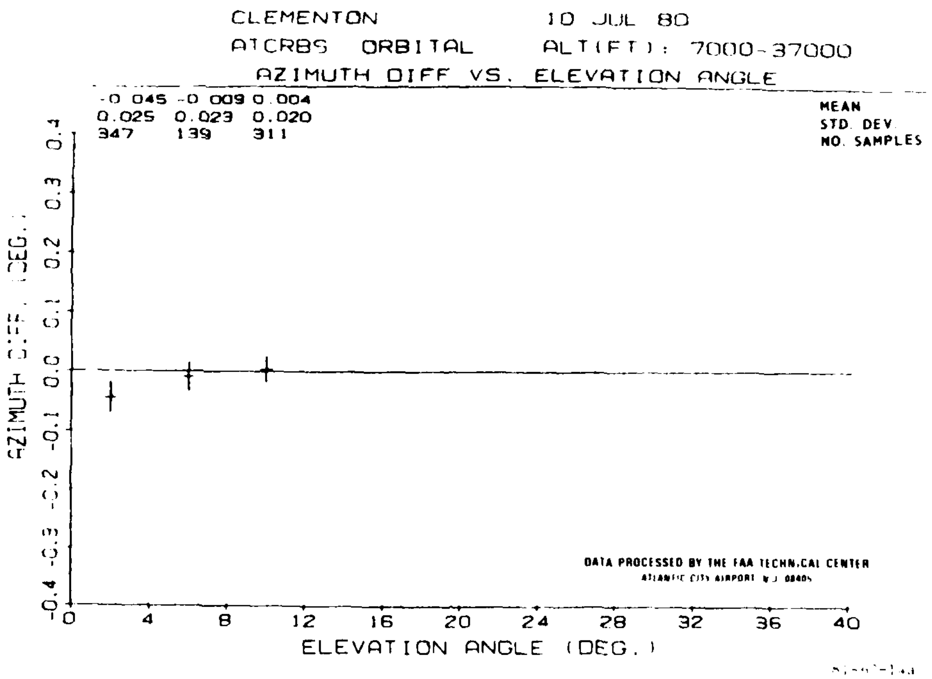


FIGURE 13. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR CLEMENTON RADIAL FLIGHTS OF JULY 24, 1980 (SHEET 2 OF 2)



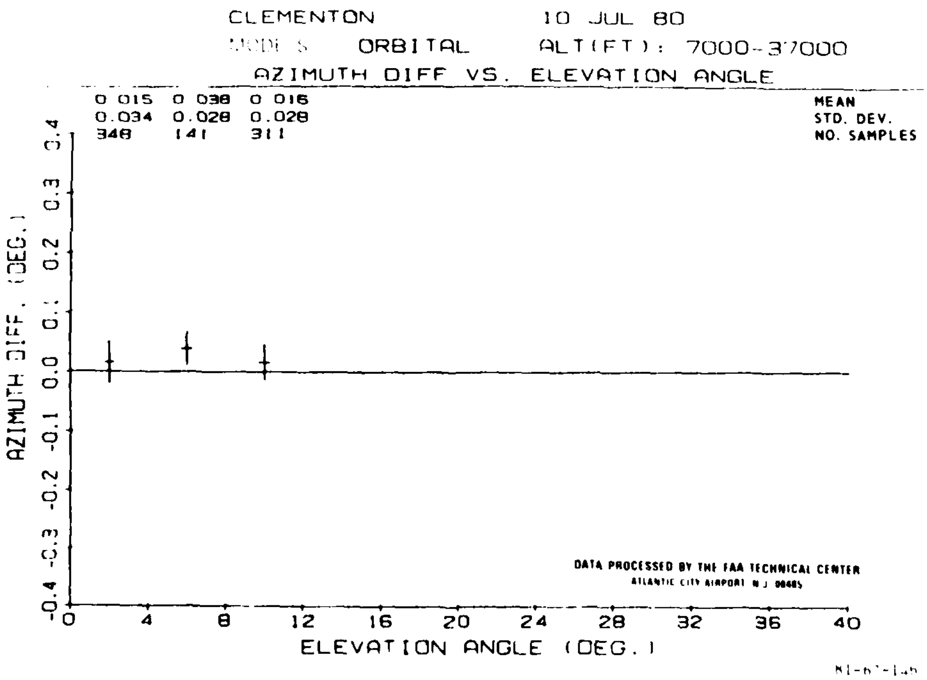
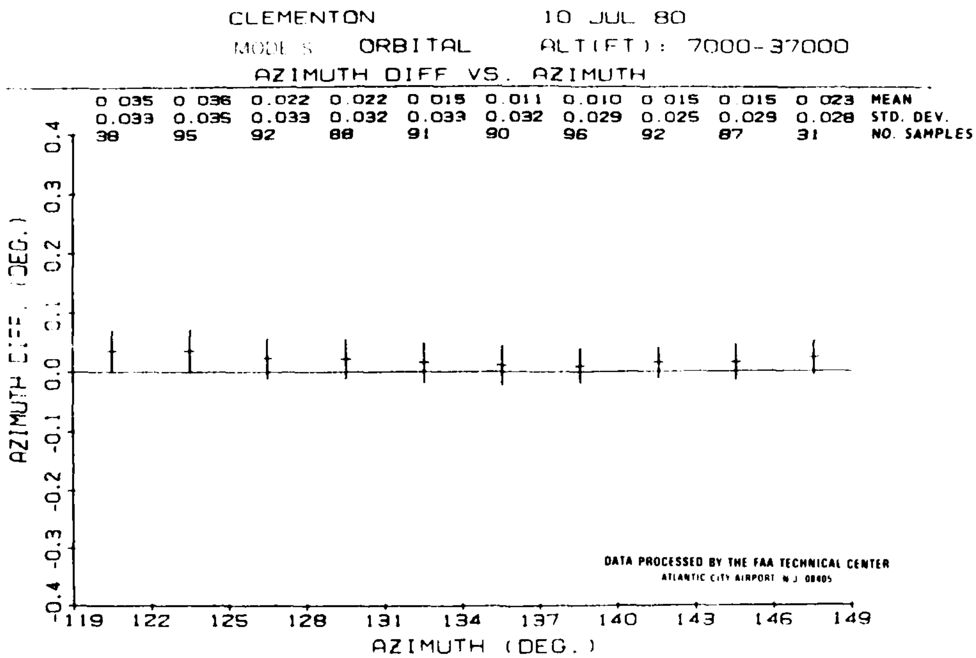


FIGURE 14. AZIMUTH RESIDUAL VERSUS ELEVATION AND AZIMUTH PLOTS FOR CLEMENTON ORBITAL FLIGHTS OF JULY 10, 1980 (SHEET 1 OF 2)



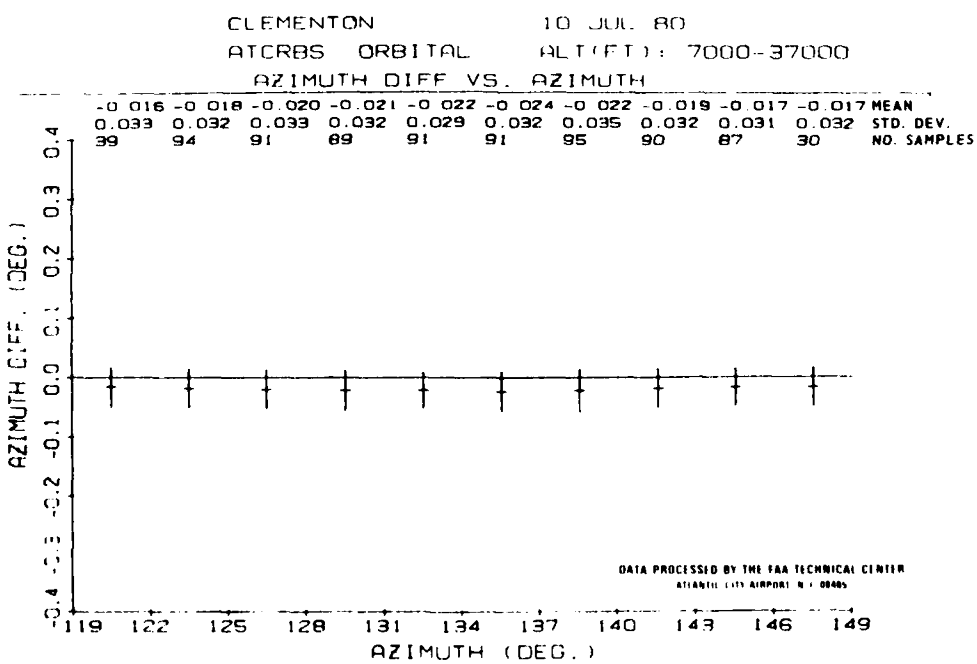


FIGURE 14. AZIMUTH RESIDUAL VERSUS ELEVATION AND AZIMUTH PLOTS FOR CLEMENTON ORBITAL FLIGHTS OF JULY 10, 1980 (SHEET 2 OF 2)

the mean or bias from run-to-run. The long term drift was detected based on bias changes from day-to-day. Figure 15 illustrates Mode S and ATCRBS azimuth residuals from both the Technical Center and the Clementon sensors. The CPME data from each site (appendix B) were superimposed on the sensor data plots, which consisted of means plus and minus a standard deviation. The CPME data displayed the same general shifting of bias as the azimuth residual data indicating that the problem was inherent in the sensor. The Clementon plots highlight the short term azimuth drift, while the Technical Center sensor plots illustrate the long term drift between the data from the two radial flight dates.

The azimuth drift problem appears to be intermittent since a weekend CPME test conducted after all accuracy data had been collected showed only minor bias variations. The accuracy data showed short term drifts of up to three azimuth units during the July 10 Clementon tests, and long term drifting of up to five units between the July 1 and July 23 tests at the Technical Center sensor.

Figure 16 illustrates the azimuth residual results for the Technical Center and Clementon sensors by presenting the data in the form of a mean ±1 standard deviation. The plots highlight the azimuth day-to-day drift. Since the highest elevation angle data collected at the Clementon sensor is about 12.5°, the azimuth residual data in figure 17 reflects only elevation angle data below 12.5° from the two sensors. This figure provides a more accurate azimuth residual comparison among sensors by removing the high elevation angle effects that bias the azimuth residual results significantly downward.

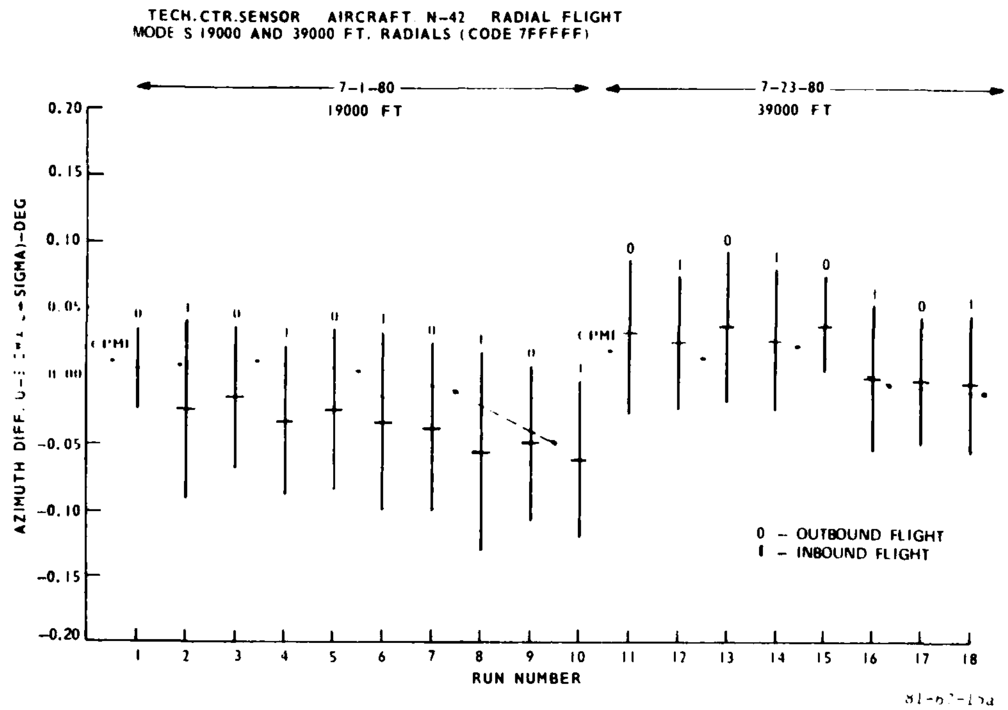
2. <u>ATCRBS Range Bias is 150 Feet Greater Than the Mode S Range Bias</u>. Considerable effort was expended to insure proper corrections were made to account for both types of transponder delays, cable delays, and antenna locations. Figure 18 summarizes the range residual results for the Technical Center and Clementon sensors and highlights the ATCRBS range bias at both sensors. The range bias difference measured between ATCRBS and Mode S targets by the Mode S sensor has been the subject of a technical investigation, described in appendix C. The conclusion drawn from that investigation is that the 150-foot bias was the result of an erroneous transponder delay measurement.

SUMMARY OF RESULTS

1. For the Technical Center and Clementon Mode S sensors, maximum standard deviation values for all test periods were 42 feet for range and 0.063° for azimuth. For the Elwood Mode S sensor, the standard deviation value exceeded the engineering requirement of 0.1° for azimuth due to front-to-back antenna differences.

2. For all sensors, range bias values varied from +33 to +217 feet for ATCRBS, and from -114 to +27 feet for Mode S reports.

3. CPME target reports indicated range bias residual less than 50 feet with maximum standard deviation values of 30 feet for the entire test period.



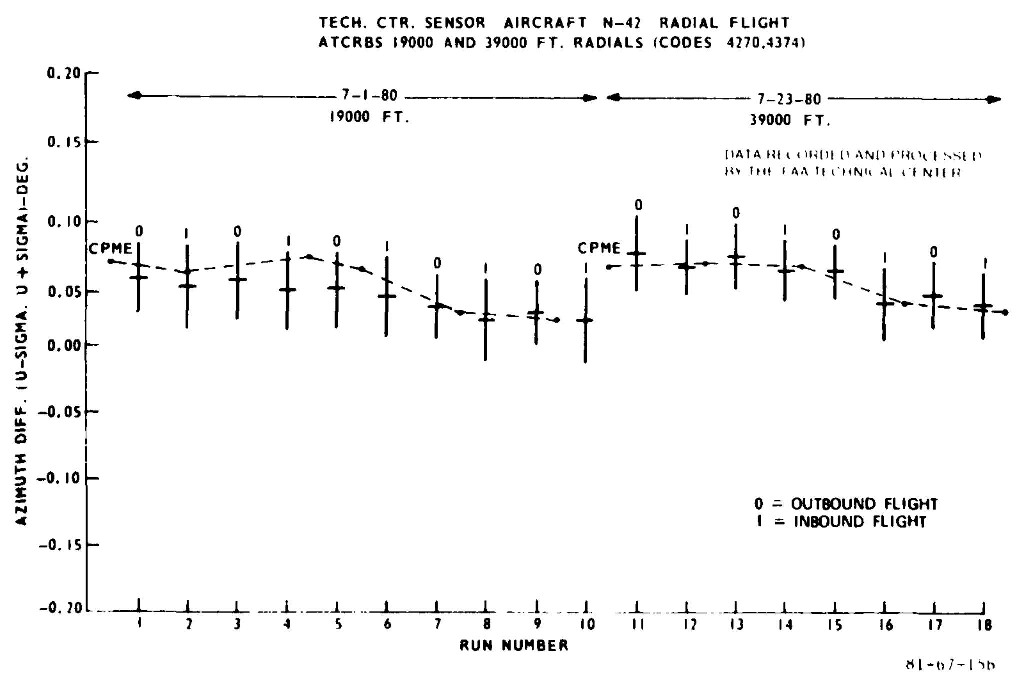
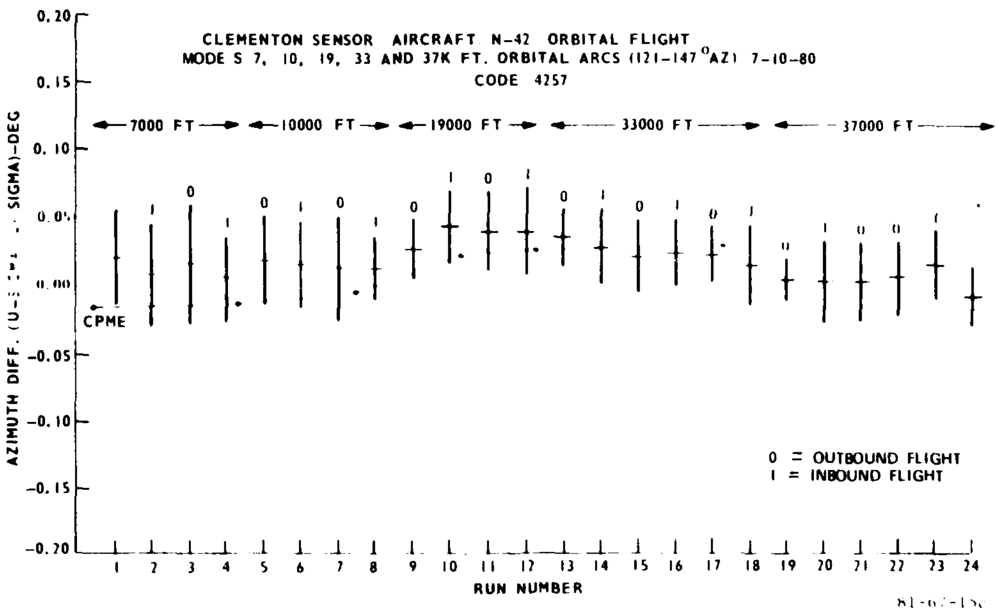


FIGURE 15. DABS AND ATCRBS AZIMUTH RESIDUALS ILLUSTRATING LONG AND SHORT TERM AZIMUTH DRIFTING (SHEET 1 OF 2)



DATA PROCESSED BY THE FAA TECHNICAL CENTER
ATLANTIC CITY AIRPORT N.J. 08405

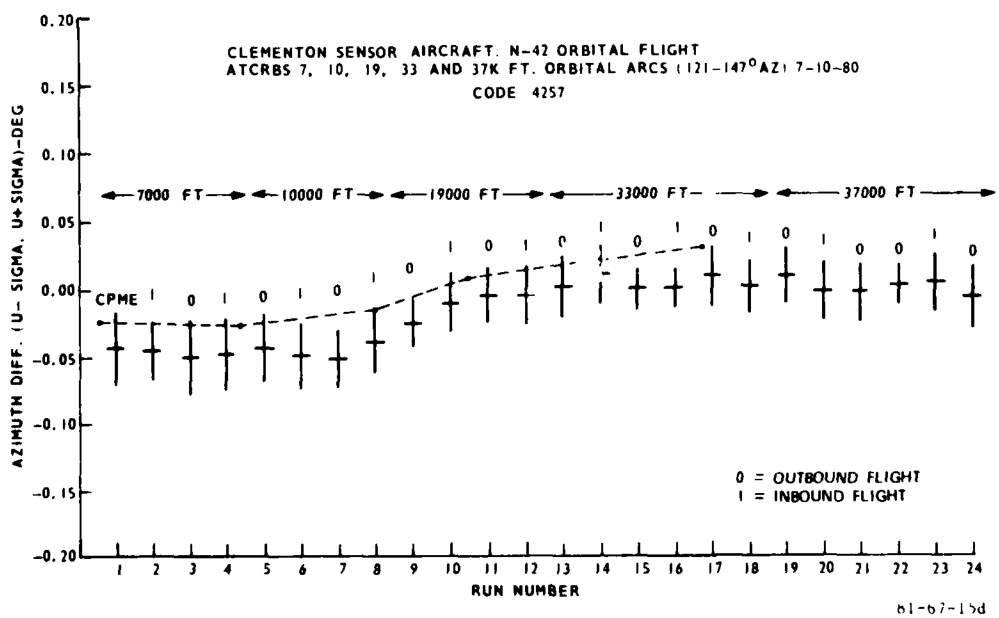


FIGURE 15. DABS AND ATCRBS AZIMUTH RESIDUALS ILLUSTRATING LONG AND SHORT TERM AZIMUTH DRIFTING (SHEET 2 OF 2)

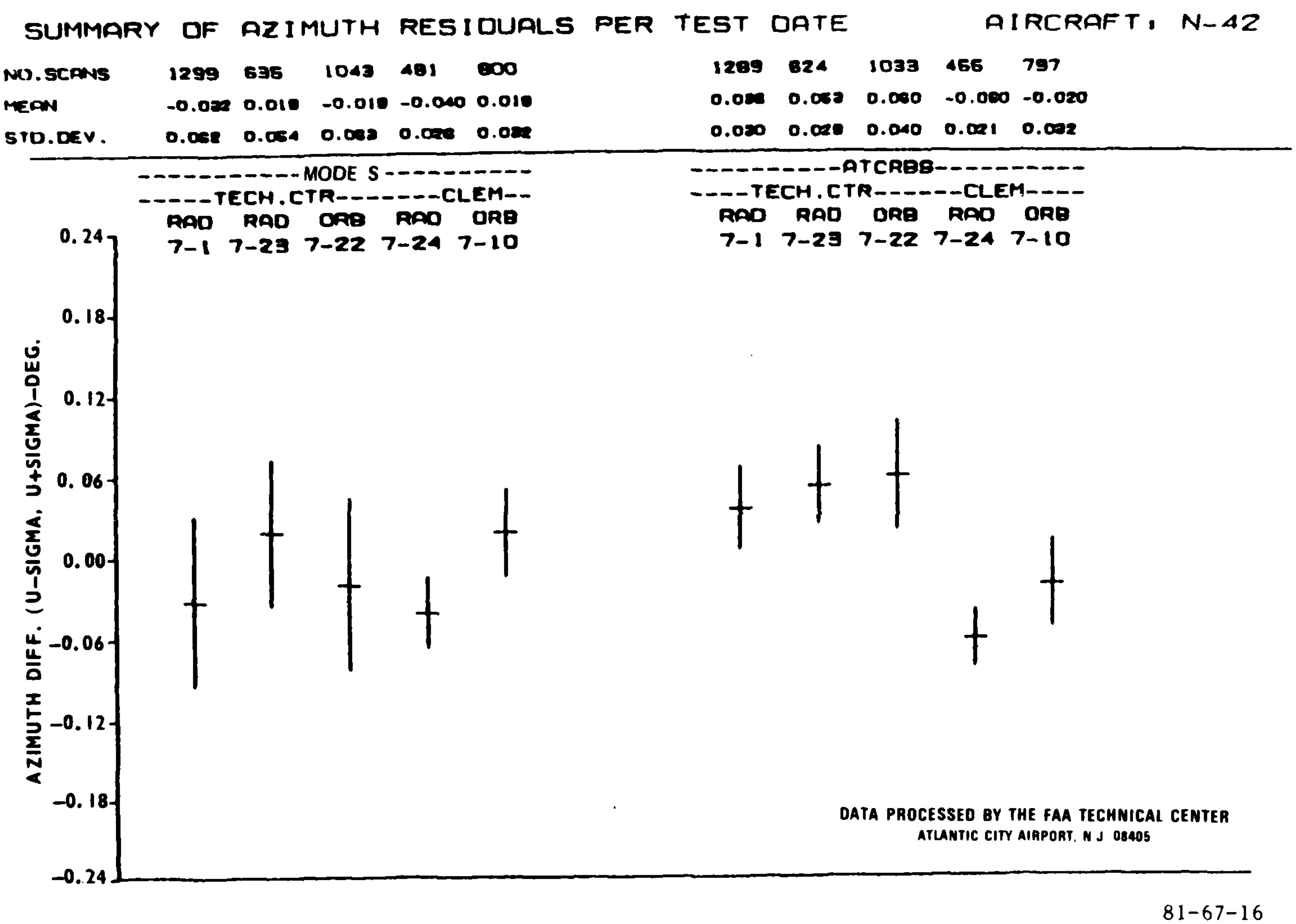
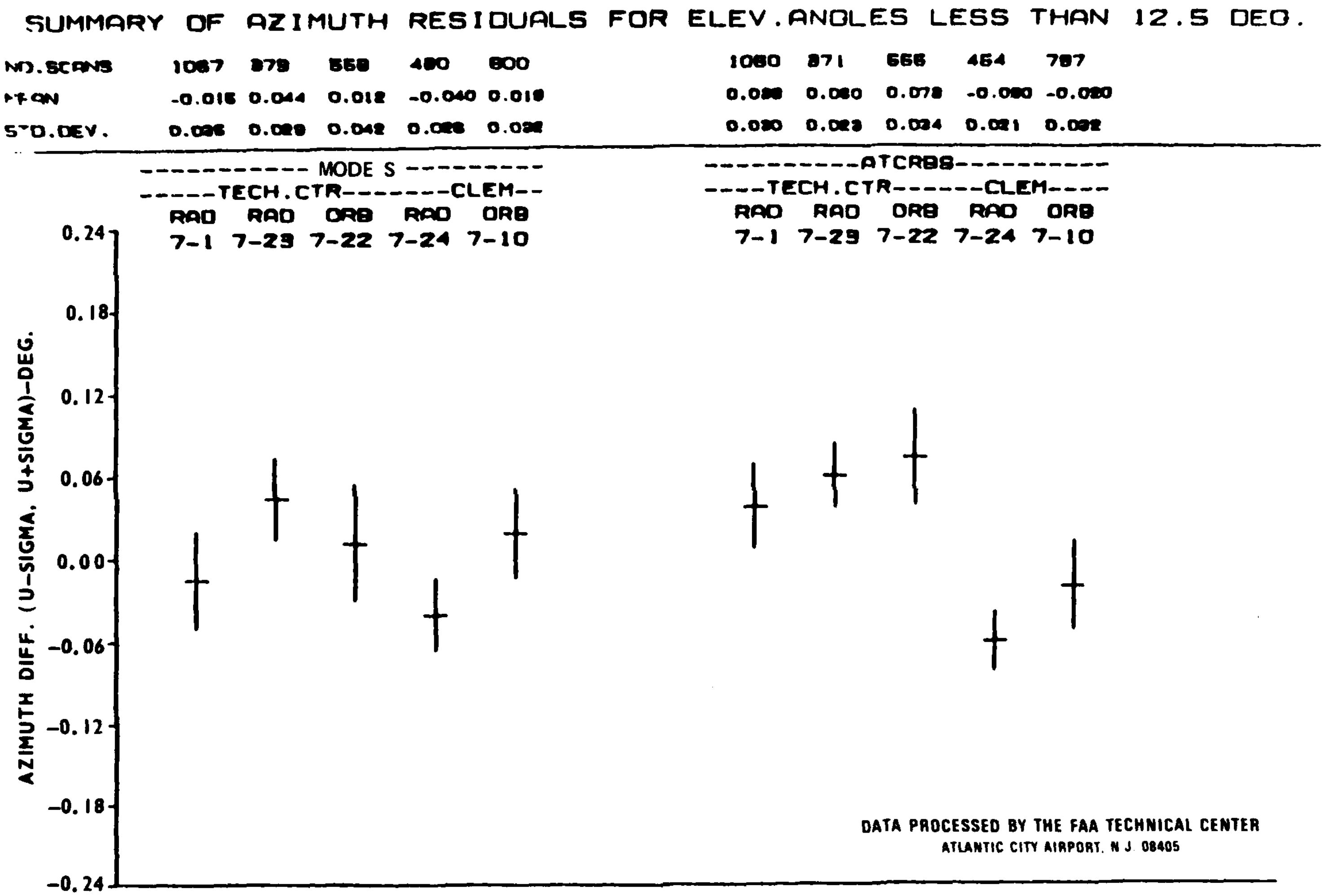
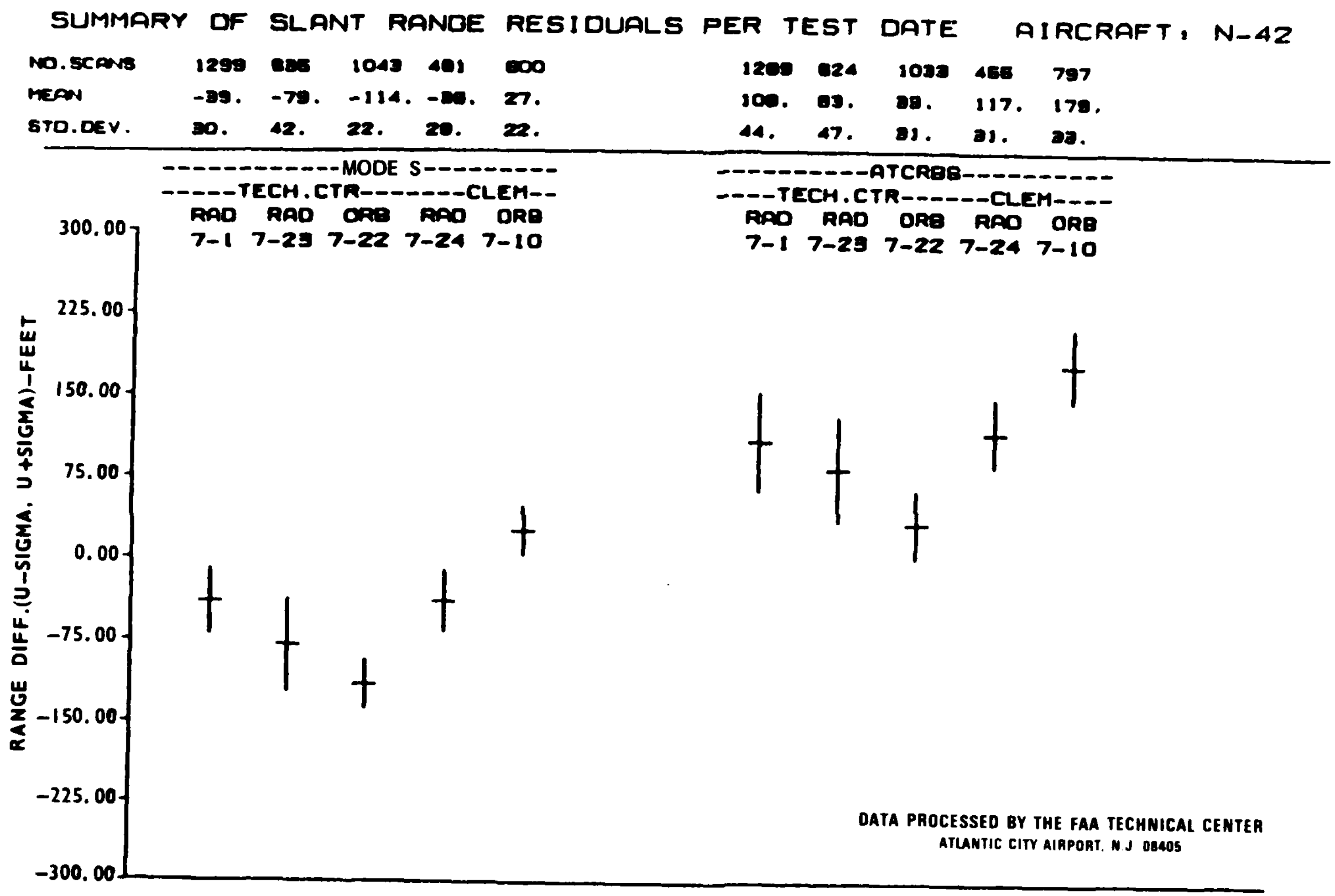


FIGURE 16. SUMMARY OF AZIMUTH RESIDUALS FOR THE TECHNICAL CENTER AND CLEMENTON SENSORS



81-67-17

FIGURE 17. SUMMARY OF AZIMUTH RESIDUALS FOR ELEVATION ANGLES LESS THAN 12.5° FOR THE TECHNICAL CENTER AND CLEMENTON SENSORS



81-67-18

FIGURE 18. SUMMARY OF RANGE RESIDUALS FOR THE TECHNICAL CENTER AND CLEMENTON SENSORS

4. CPME and aircraft data both depicted occasional short- and long-term azimuth drift, which increased the overall standard deviation. The short-term drift, as noted for the CPME target (up to two azimuth units), was reflected in the 0.063° standard deviation for the aircraft data.

5. Azimuth bias values changed significantly at higher elevation angles (above 20°) for Mode S reports as compared to ATCRBS reports. For the Technical Center sensor, Mode S azimuth bias was -0.186° for elevation angles between 20° and 30° and -0.021° for angles between 4° and 20°.

6. Range bias values showed an increasing error as a function of slant-range from the sensor of approximately 1 foot per nmi for Mode S and 1 1/2 feet per nmi for ATCRBS data.

7. At the en route radar facility at Elwood, where a front and back antenna combination was used to produce reports at the desired half-scan rates, the azimuth bias values from the CPME target reports differed as much as three azimuth units (0.066°). This front-to-back antenna azimuth difference exceeded 0.3° at high elevation angles for ATCRBS data.

CONCLUSIONS

Based on the test results obtained during the test and evaluation of the Mode S (formerly the Discrete Address Beacon System (DABS)) it is concluded that:

1. The range and azimuth accuracy of the Mode S sensor, as determined from calibration performance monitoring equipment (CPME) reports, is within the requirements specified in the engineering requirement FAA-ER-240-26.

2. The range and azimuth accuracy (one standard deviation) for aircraft target reports is within specified requirements at the terminal Mode S sensors.

3. Large differences (greater than 150 feet) in range-bias residuals exist between ATCRBS and Mode S target reports and are attributed to faulty transponder delay measurements (appendix C).

4. Azimuth differences (greater than 0.1°) between front and back antennas at the en route radar facility are attributed to alignment and software errors.

5. The ATCRBS range bias residual for the CPME is less than the range bias measured for test aircraft.

6. The range bias error which increases as a function of slant range is attributed to the transponder delay characteristics for various power settings.

RECOMMENDATIONS

Based on the test results obtained during the test and evaluation of the Mode S (formerly the Discrete Address Beacon System (DABS)) it is recommended that:

1. If additional accuracy is required, software should be developed to adjust range and azimuth residuals based on the mathematical models that reflect range or azimuth residuals as a function of slant-range, elevation angle, or calibration performance monitoring equipment (CPME). This change would allow for improved azimuth accuracies at high elevation angles and would correct for range differences due to attenuation.

2. Decrease the slant-range quantization from approximately 60 to 30 feet by permitting one additional bit in range reports. This change would enable improved accuracy reporting without excessive costs for additional memory since the 16-bit word already exists.

REFERENCES

1. Federal Aviation Administration, Discrete Address Beacon System - Phase II, Engineering Requirement, FAA-ER-240-26, November 1, 1974.

2. Purcell, P. R., Surveillance Position Accuracy of the Discrete Address Beacon System, MITRE Corp., MTR-80N00002, April 1980.

3. Drouilet, P. R., DABS: A System Description, Lincoln Laboratory, MIT Report ATC-42, FAA-RD-74-189, November 18, 1974.

4. Orlando, V. A. and Drouilhet, P. R., Discrete Address Beacon System Functional Description, Lincoln Laboratory, MIT Report ATC-42A, FAA-RD-80-41, April 1980.

5. Reiner, D., and Vandevenne, H. R., Provisional Message Formats for the DABS/NAS Interface (Revision 1), Lincoln Laboratory, MIT Report ATC-33 (Rev. 1), FAA-RD-74-63A, October 10, 1974.

6. Luciani, V. J., NAFEC Range Instrumentation Systems, FAA Report, FAA-NA-79-32, February 1980.

APPENDIX A

TEST RESULTS AND ANALYSIS OF EN ROUTE (ELWOOD) SENSOR

The Elwood en route sensor tests consisted of one radial and one orbital flight. The radial flight was flown from about 13.5 nautical miles (nmi) from the sensor along a 151° true north radial. The orbital arc flights were flown from about 129° to 173° azimuth from the sensor. The orbital arcs were conducted at altitudes ranging from 3,500 to 35,000 feet, thereby, producing elevation angle data up to about 20°. A summary of azimuth and range residuals for the test data are contained in table A-1.

The azimuth residual data showed extremely large Air Traffic Control Radar Beacon System (ATCRBS) standard deviations. Also, the large difference in azimuth mean between ATCRBS and Mode S was caused by a problem in the Elwood sensor software affecting ATCRBS reports emanating from the back face of the front/back antenna configuration. A trouble report has been issued and is being processed. The Mode S slant range data showed modest differences, but the ATCRBS range data contained a very large bias exceeding 150 feet. However, this bias is attributed to faulty transponder delay measurements (appendix C).

The ATCRBS azimuth residual standard deviation is much greater at high elevation angles, also due to the problem with the back face of the antenna. The back face antenna problem also affected the Mode S data with azimuth bias differences between front and back faces exceeding 0.1° at high elevation angles where the problem was magnified. The ATCRBS azimuth bias differences at high elevation angles exceed 0.3° between the front and back antenna faces.

Figures A-1 and A-2 contain azimuth and slant range histograms for radial and orbital flights. Figures A-3 and A-4 contain plots of azimuth and range residuals for radial and orbital flights. The azimuth residuals are affected by changes in azimuth as illustrated in the figure A-4 plots. This effect, which is more prominent in the Mode S data, did not occur at either of the other two sensors. Antenna alignment is the suspected cause of the problem.

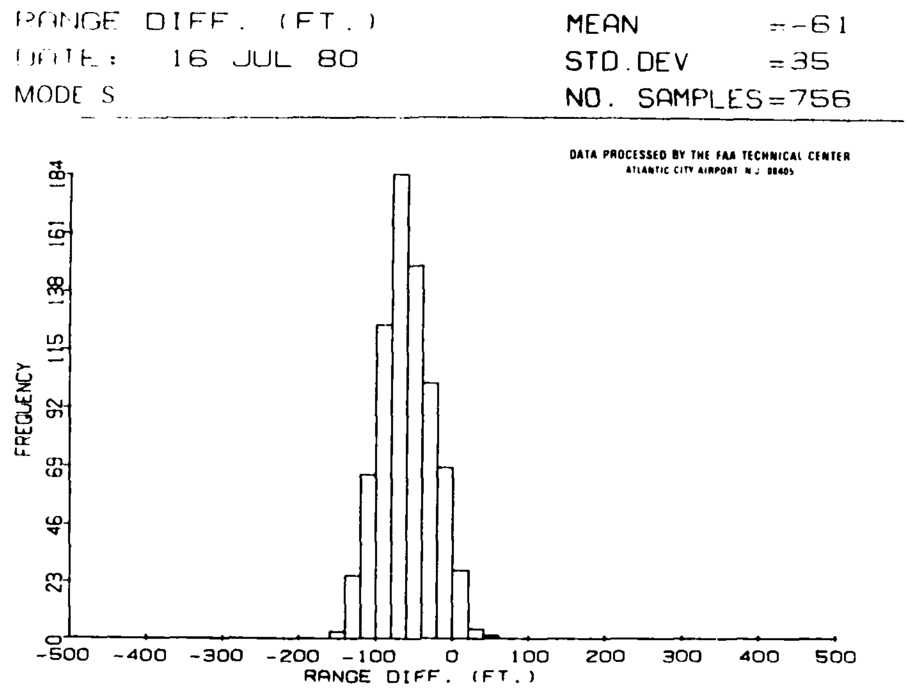
TABLE A-1. ELWOOD SENSOR

Azimuth Residuals (degrees)

			Mode S			ATCRBS		
Date (1980)	Test Flights	No. Flights	No. Samples	Mean (deg)	Std Dev (deg)	No. Samples	Mean (deg)	Std Dev (deg)
7/16	Radials	22	756	-0.132	0.058	878	-0.025	0.101
7/9	Orbital/Arcs	20	585	0.121	0.093	576	-0.032	0.111

Slant Range Residuals (feet)

			Mode S			ATCRBS		
Date (1980)	Test Flights	No. Flights	No. Samples	Mean (ft)	Std Dev (ft)	No. Samples	Mean (ft)	Std Dev (ft)
7/16	Radials	22	756	-61	35	878	162	60
7/9	Orbital/Arcs	20	585	5	27	576	217	37



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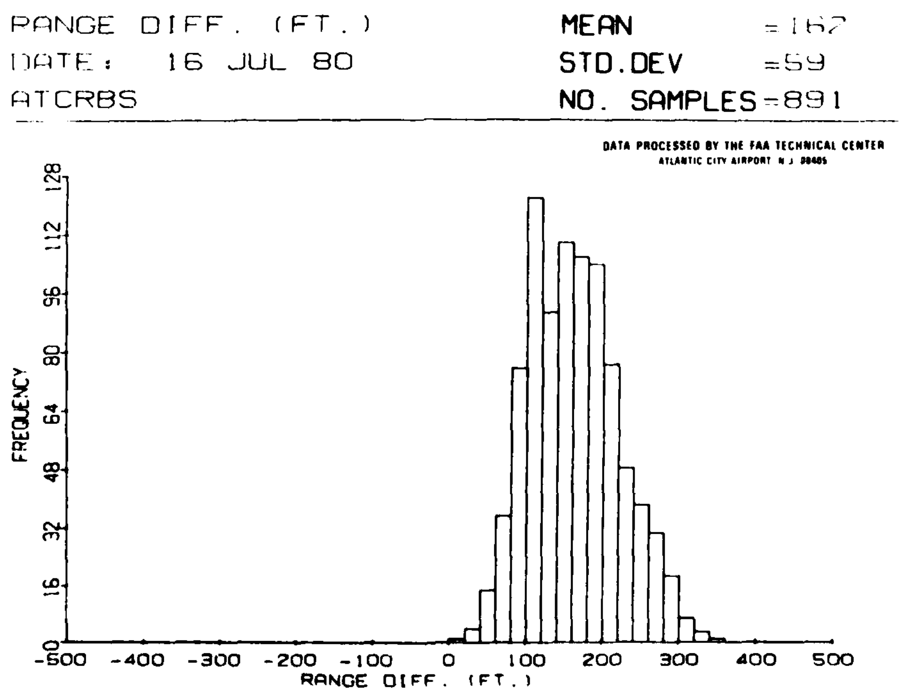
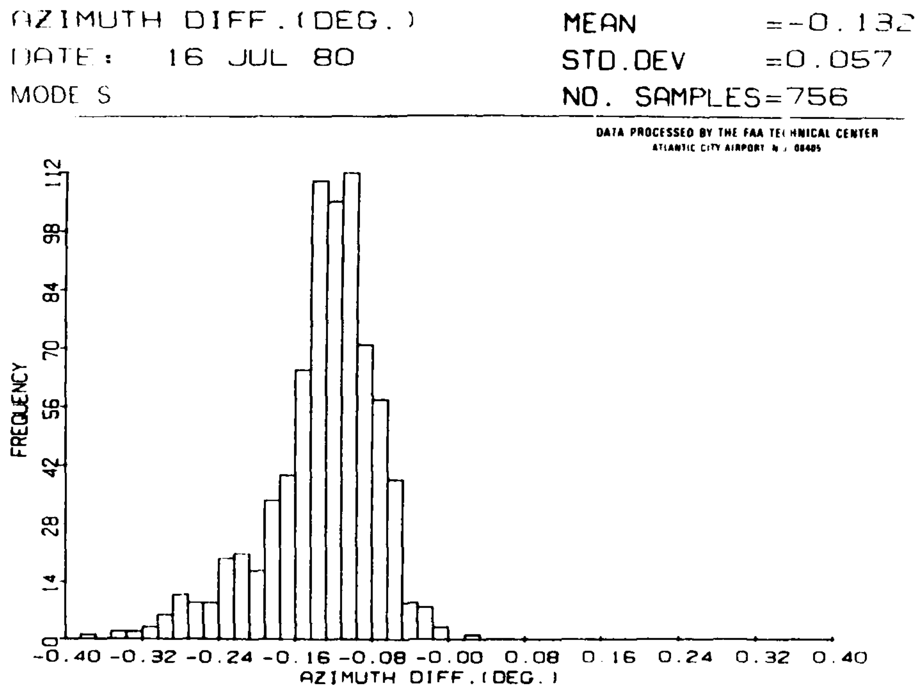
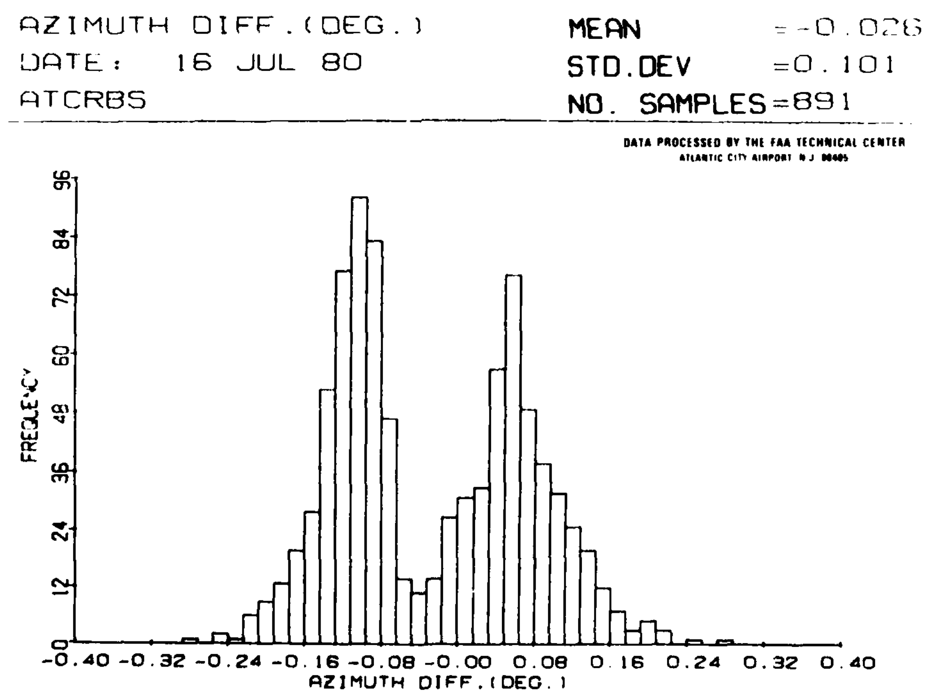


81-67-A-1b

FIGURE A-1. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR ELWOOD SENSOR RADIAL FLIGHTS OF JULY 16, 1980 (SHEET 1 OF 2)

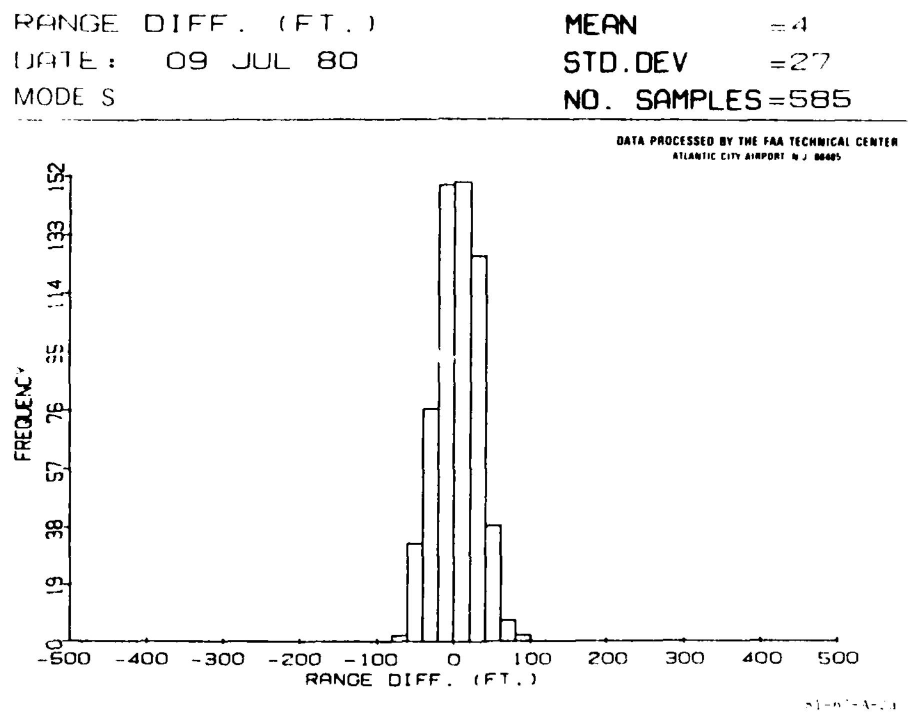


81-67-A-1c



81-67-A-1d

FIGURE A-1. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR ELWOOD SENSOR RADIAL FLIGHTS OF JULY 16, 1980 (SHEET 2 OF 2)



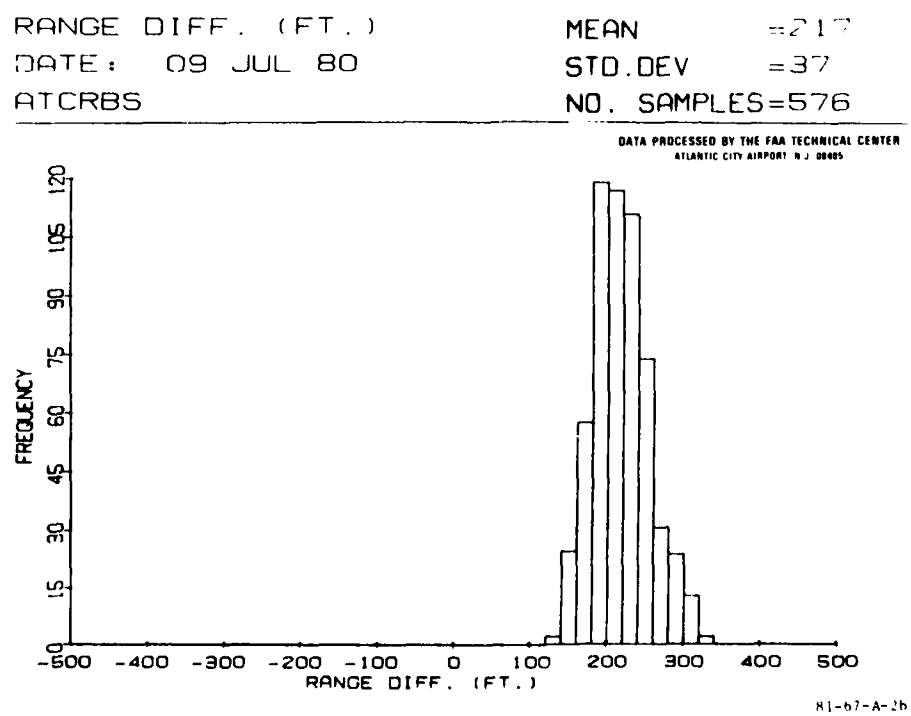
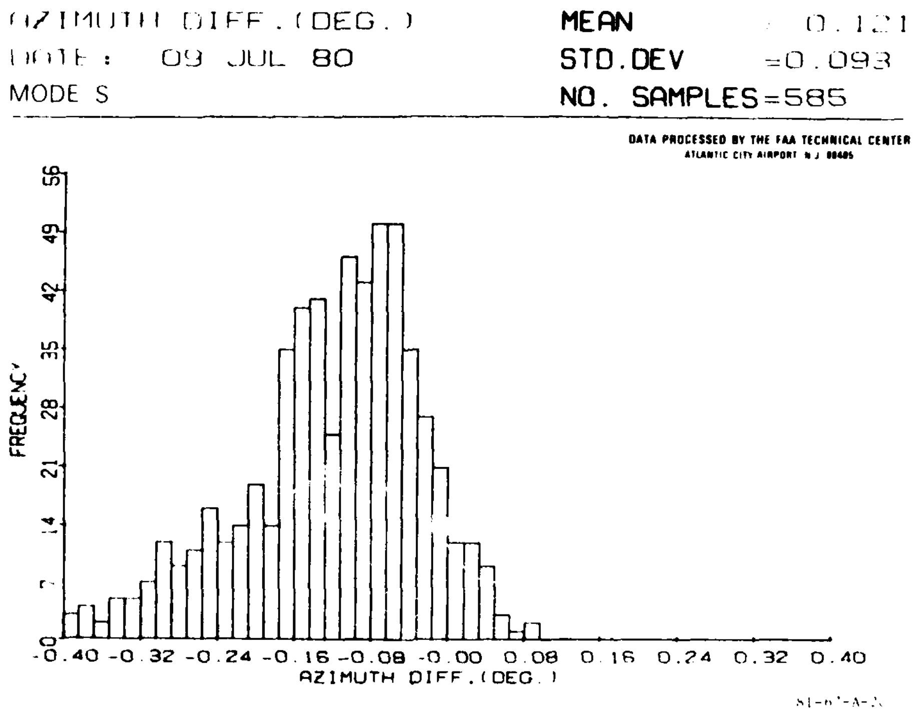
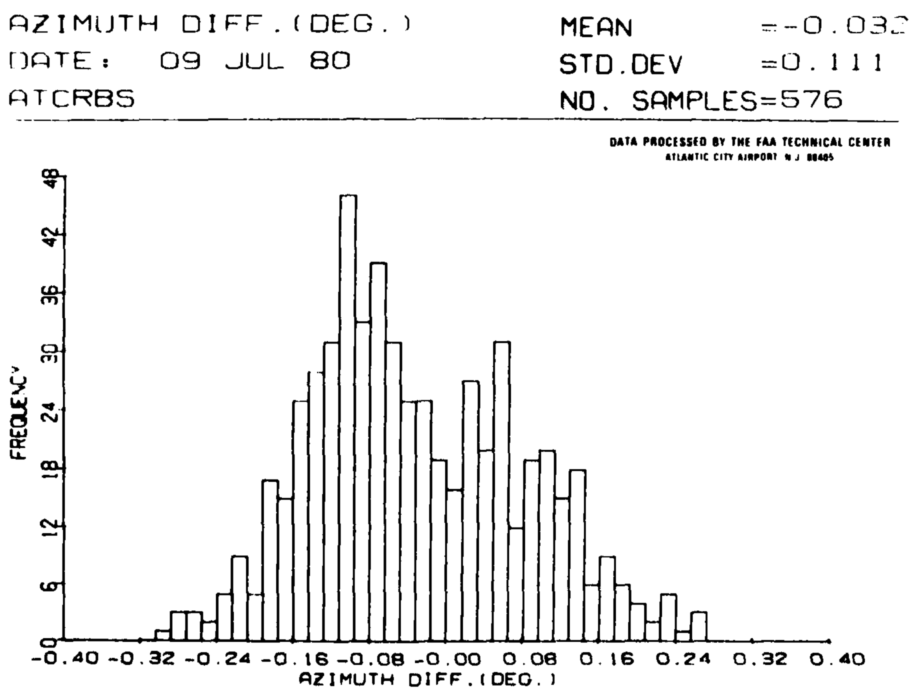


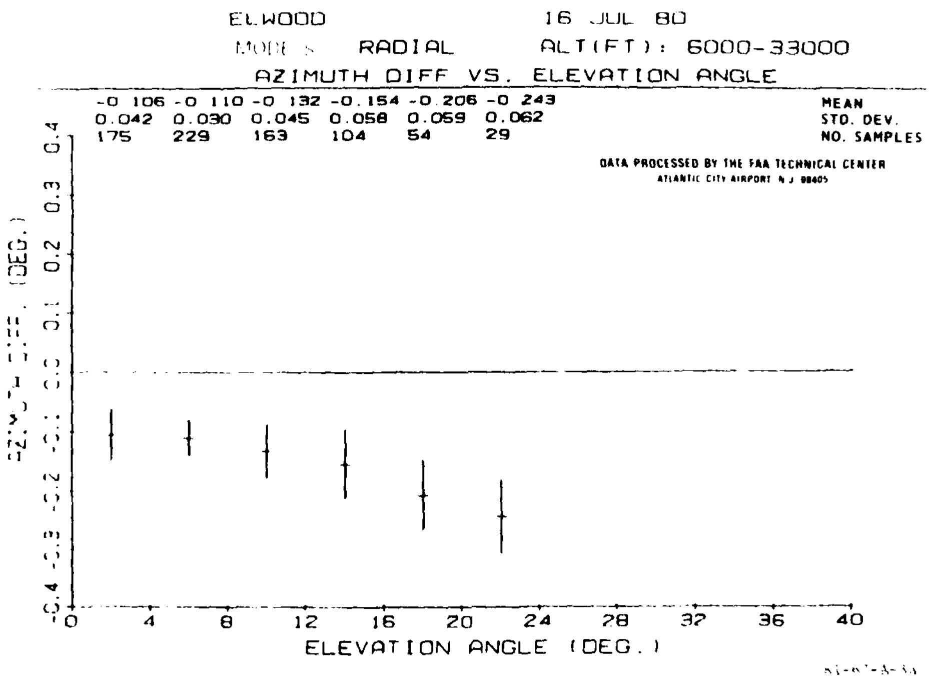
FIGURE A-2. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR ELWOOD SENSOR ORIBITAL FLIGHTS OF JULY 9, 1980 (SHEET 1 OF 2)





81-67-A-2d

FIGURE A-2. AZIMUTH AND RANGE RESIDUAL DATA HISTOGRAMS FOR ELWOOD SENSOR ORIBITAL FLIGHTS OF JULY 9, 1980 (SHEET 2 OF 2)



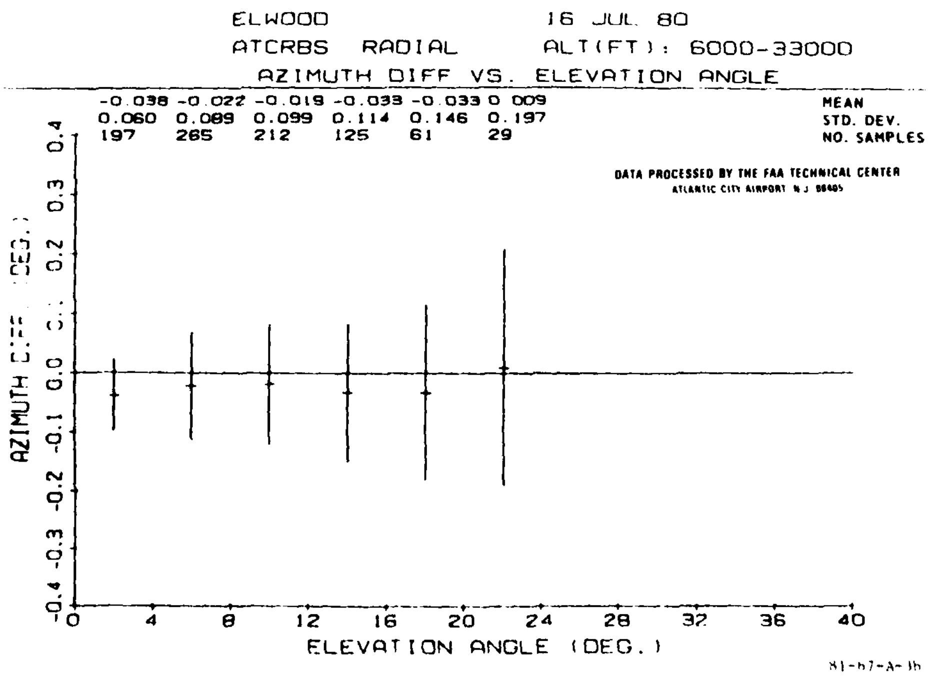
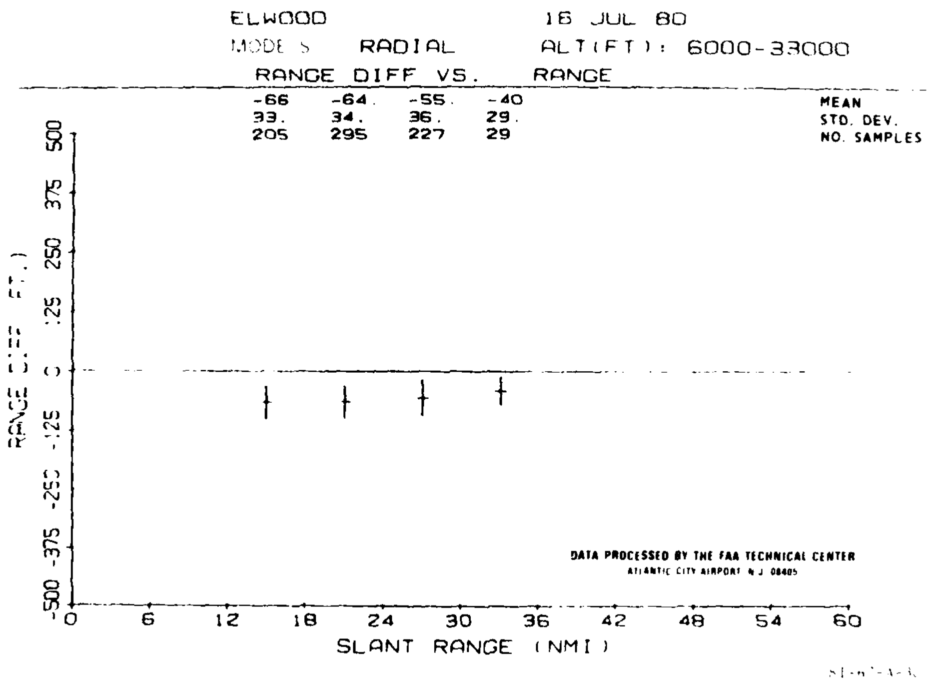


FIGURE A-3. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR ELWOOD RADIAL FLIGHTS OF JULY 16, 1980 (SHEET 1 OF 2)



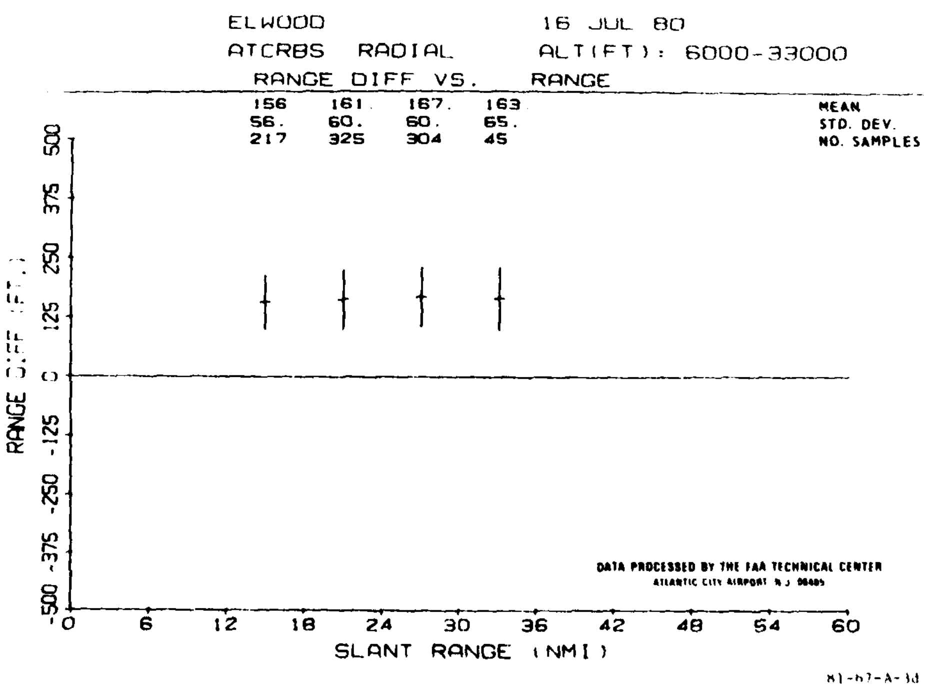
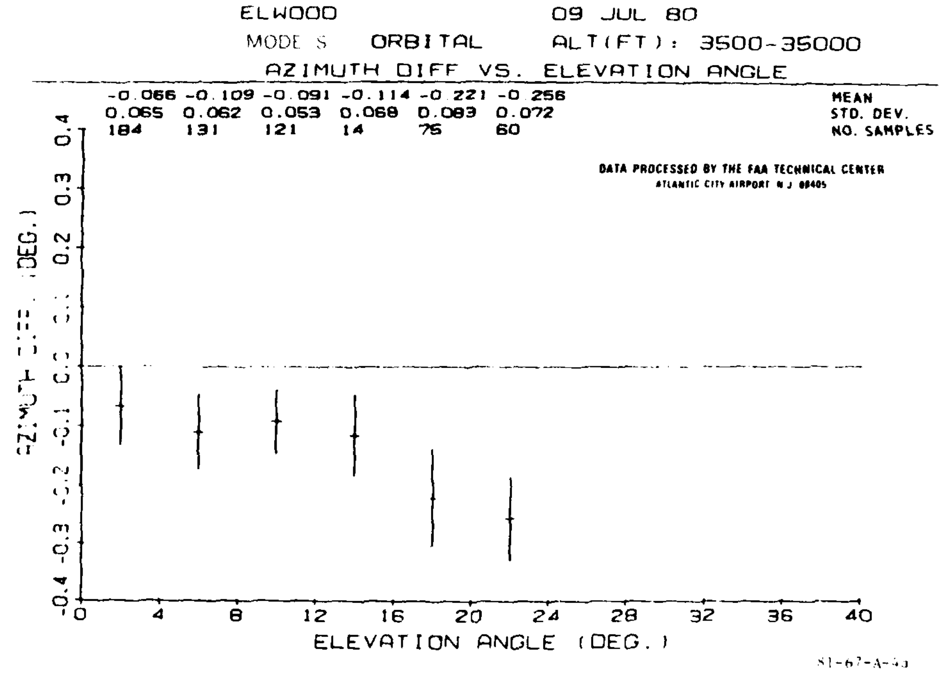


FIGURE A-3. AZIMUTH RESIDUAL VERSUS ELEVATION AND RANGE RESIDUAL VERSUS RANGE PLOTS FOR ELWOOD RADIAL FLIGHTS OF JULY 16, 1980 (SHEET 2 OF 2)



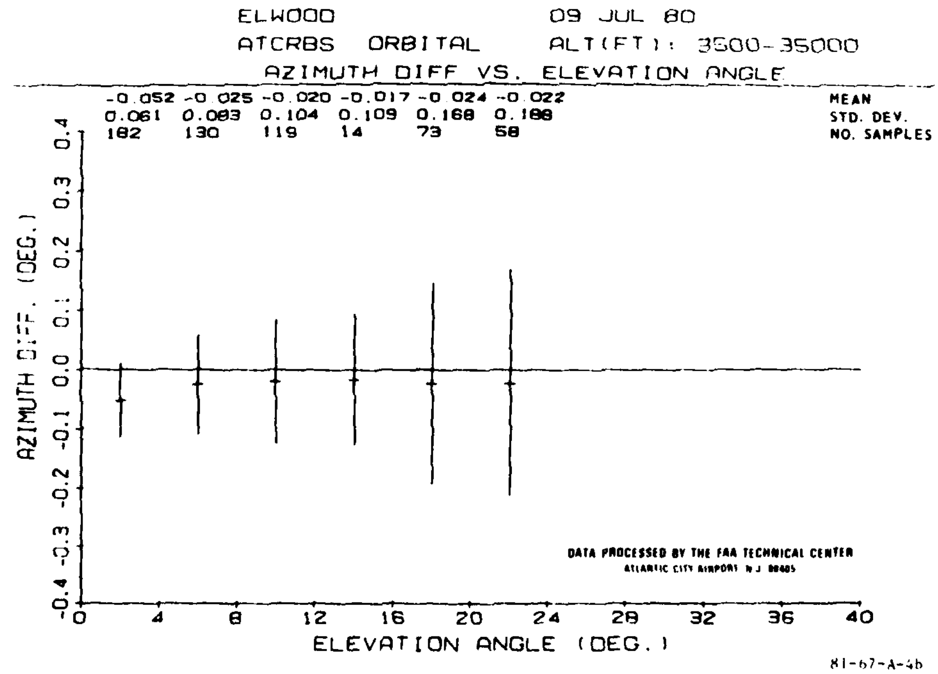
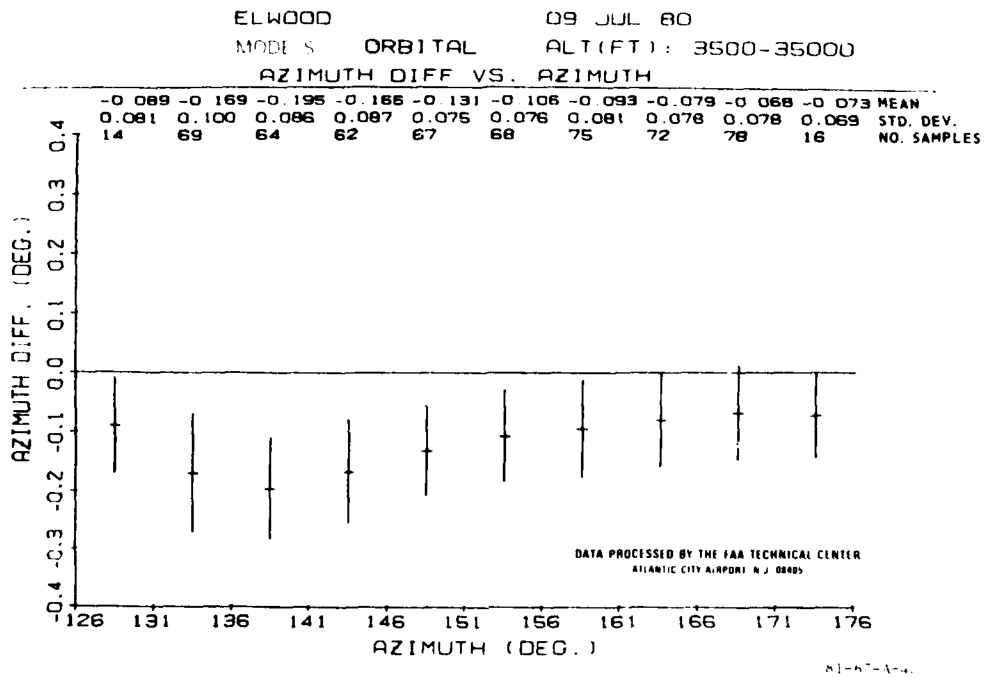


FIGURE A-4. PLOTS OF AZIMUTH RESIDUALS VERSUS ELEVATION AND AZIMUTH ANGLES FOR ORBITAL FLIGHTS OF JULY 9, 1980 (SHEET 1 OF 2)



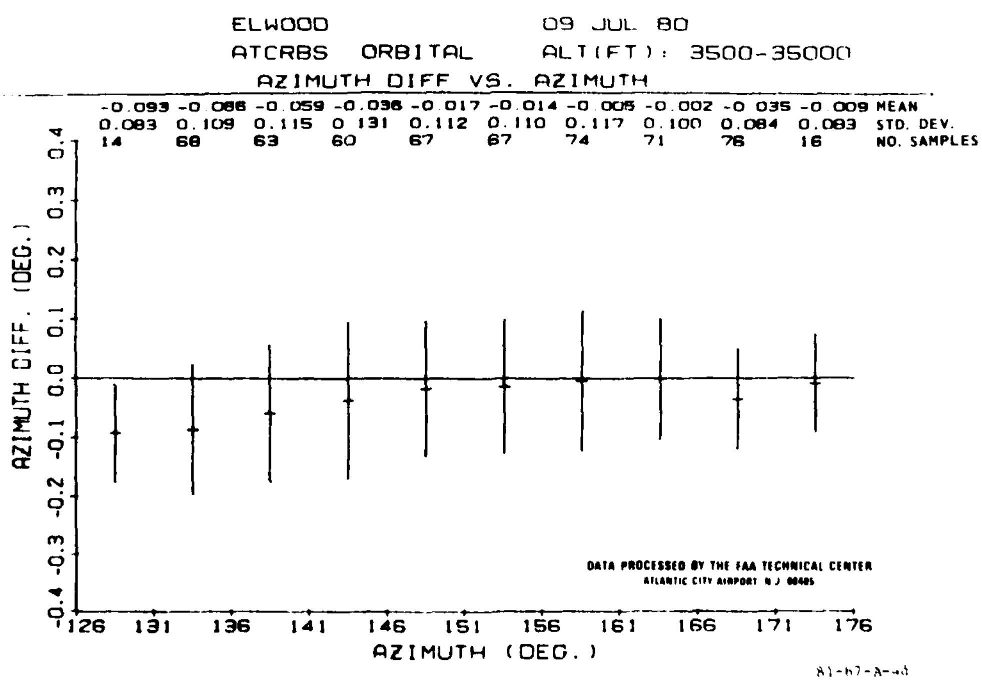


FIGURE A-4. PLOTS OF AZIMUTH RESIDUALS VERSUS ELEVATION AND AZIMUTH ANGLES FOR ORBITAL FLIGHTS OF JULY 9, 1980 (SHEET 2 OF 2)

APPENDIX B

CALIBRATION PERFORMANCE MONITORING EQUIPMENT ACCURACY FOR ALL THREE SENSORS

During all flight tests related to system accuracy, target reports from the Calibration Performance Monitoring Equipment (CPME) were recorded and later analyzed for the purpose of determining the "static" accuracy and stability of the sensor. Since the survey position of each CPME and its delay characteristics are utilized in the initial calibration of the range and azimuth estimation functions, its performance during the tests are considered significant since it can be presumed that any degradation of CPME performance will be reflected in the aircraft data. In addition to providing a quality control check, the CPME target reports constitute a true sensor-only performance that is independent of any data collection errors.

Both Air Traffic Control Radar Beacon System (ATCRBS) and Mode S reports from the CPME were continuously recorded to permit comparison with the effective range and azimuth and, thus, produce output statistics for a 30-scan interval once every 30 minutes. This provided a quick-look at sensor performance when analyzing the dynamic test results.

RANGE ACCURACY.

Table B-1 depicts the slant-range error values for both the ATCRBS and Mode S reports from the CPME during the entire period of time that data were collected with the aircraft transponders. Note that for all sensors, the range error, as reported by the CPME, was less than the minimum incremental change (60 feet) available at each sensor, with the maximum mean error value being -42 feet for ATCRBS reports at the Clementon sensor.

A review of the individual scan reports indicated that the minimum change that occurred in range reporting by any sensor was in increments of 60 feet, which is twice the value specified by the engineering requirements. The reason for this was a software design that utilized two range units as the least significant bit.

AZIMUTH ACCURACY.

Table B-2 depicts the azimuth error values for both ATCRBS and Mode S reports from the CPME during the entire period of time that data were collected with the aircraft transponders. Note that, in all cases, the azimuth error was less than three azimuth units (0.066°). The least incremental change noted in the azimuth bias values, when analyzed on an individual scan basis, was equal to the required value of one azimuth unit (0.022°).

The relatively high value of standard deviation for the Technical Center sensor was apparently due to a short-term drift (up to two azimuth units) that occurred during the test period. This effect was noted during one test period associated with the Clementon sensor. For the Elwood sensor, there was a difference, on a scan-by-scan basis, of up to three azimuth units between the front and back antennas, thus, resulting in a relatively high value of standard deviation. This difference at the CPME is significant since the aircraft data showed a high dispersion value, which was apparently due to this difference between the front and back antennas at the higher elevation angles.

TABLE B-1. RANGE ERROR (FEET) CPME TARGET REPORTS

Sensor Test Flight Dates (1980)	Mode S No. Samples	Mode S Mean (ft)	Mode S Std Dev (ft)	ATCRBS No. Samples	ATCRBS Mean (ft)	ATCRBS Std Dev (ft)
Technical Center						
7/1	1,964	-12	30	1,607	-18	12
7/22	2,270	-12	30	1,824	-18	6
7/23	1,551	-18	30	1,272	-24	12
Clementon						
7/10	3,044	-12	30	2,771	-42	12
7/24	1,450	-18	30	1,436	-42	6
Elwood						
7/9	1,956	-12	12	1,951	-24	18
7/16	2,583	-12	0	2,578	-24	18

Note: Range value representing least significant bit (LSB) = 60 ft for all sensors

TABLE B-2. AZIMUTH ERROR (DEGREES) CPME TARGET REPORTS

Sensor Test Flight Dates (1980)	Mode S			ATCRBS		
	No. Samples	Mean (deg)	Std Dev (deg)	No. Samples	Mean (deg)	Std Dev (deg)
Technical Center						
7/1	1,964	-0.013	0.036	1,607	0.047	0.022
7/22	2,270	-0.034	0.036	1,824	0.064	0.017
7/23	1,551	0.002	0.031	1,272	0.053	0.020
Clementon						
7/10	3,044	0.005	0.014	2,771	0.005	0.027
7/24	1,450	-0.064	0.022	1,436	-0.044	0.017
Elwood						
7/9	1,956	0.010	0.037	1,951	0.004	0.027
7/16	2,583	0.006	0.035	2,578	-0.003	0.023

Note: Azimuth value representing least significant bit (LSB) = 0.022°

APPENDIX C

INVESTIGATION OF RANGE BIAS DIFFERENCE BETWEEN AIR TRAFFIC CONTROL RADAR BEACON SYSTEM AND MODE S TARGETS

The 150-foot range bias difference between Mode S and Air Traffic Control Radar Beacon System (ATCRBS) targets as measured by the Mode S sensor was investigated. A number of areas were investigated in an effort to eliminate possible sources of the bias. The following results were obtained:

1. The data reduction from all flight tests was verified.

2. The computer programs were verified.

3. Three Mode S and three ATCRBS transponders were range-tested at the Calibration Performance Monitoring Equipment (CPME) antenna location to determine whether the sensor introduced a bias.

4. A range quantization test using two transponders, the CPME antenna, and varying cable lengths verified the 60-foot range quantization that was observed from the flight tests.

5. A radial flight was conducted at the Technical Center in March 1981 using one of the Mode S and ATCRBS transponders tested at the CPME (see item 3). The difference in corrected range values for the Mode S and ATCRBS transponders was 12 feet.

6. On June 9, 1981 the ATCRBS and the Mode S transponders that were used for the July 1980 tests wer. located and tested to remeasure the delay times. These new measurements showed an approximate 150-foot effective range difference from the original measurements.

Based on the results of this investigation, it appears that the cause of the 150-foot bias is that either the Mode S (serial 203) or the ATCRBS (serial 34) transponder delay was measured incorrectly. These two transponders were used on the Technical Center Convair 880 for all test flights. Efforts to remeasure these transponder delays was not possible because the Convair 880, on which the test ATCRBS transponder was installed, was transferred to the United States Navy and relocated shortly after the last flight test. When the transponders were located, the delays that were measured at a -24 decibels above 1 milliwatt (dBm) power setting were 3.056 microseconds for the ATCRBS transponder (serial 34) and 127.900 microseconds for the Mode S transponder (serial 203). It was noted that the ATCRBS transponder delay increased as the input signal level was attenuated. The results of these measurements show the equivalent of about a 1.5-foot per nautical mile change, which agrees with that observed in the test data analyzed.

The ATCRBS measured delay at -24 dBm showed only a 6-nanosecond difference with the 3.050-microsecond delay described in this report. The 6-nanosecond difference equates to only about 3 feet in range. However, the Mode S transponder showed a 330-nanosecond difference from the 128.230-microsecond delay described in this report. That delay difference equates to 162-feet which would explain the 150-foot bias that was observed in the tests. Although this explains the bias and investigations revealed no readjustments of the transponders since the July 1980 tests, it must be noted that these delays were measured 10 months after the last test flight.